Evidence for an Anomalous Like-sign Dimuon Charge Asymmetry

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Why the Big Fuss?

The New York Times

A New Clue to Explain Existence

TIME

Big News About Small Particles. And Why You Care

SCIENTIFIC AMERICAN

FORTE

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Fermilab Finds New Mechanism for Matter's Dominance over Antimatter

HABERCİNİZ

SİZİN HABERCİNİZ BİZİZ

Noi descoperiri în misterul antimateriei

RL România liberă.ro

Telegraph

Haber: Evrendeki Dengelere Yeni Denklem

Atom smasher offers new clue to mystery of universe's formation

Почему мы существуем: как материя побеждает антиматерию

НОВОСТИ САМАРА сегодня

Ежедневная интернет-газета

中国新闻网 中新网

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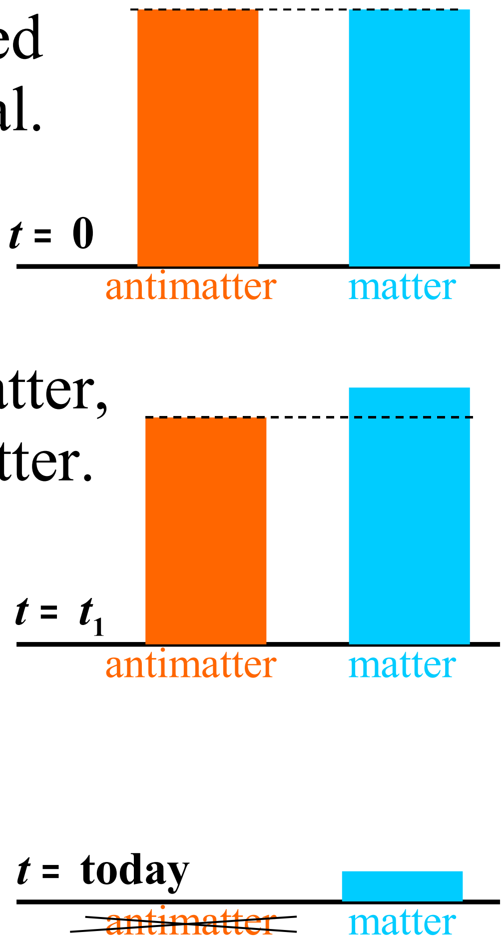
宇宙何以充斥物质而不是反物质？

europapress.es

El Tevatrón halla una pista para entender la composición del Universo

Why Asymmetry Matters...

- The universe that we observe is matter dominated, but...
- ...the number of particles and antiparticles produced during the Big Bang is expected to have been equal.
- **For some reason matter becomes more abundant in the early stages of the universe.**
- After annihilation of the bulk of matter and antimatter, we are today left with only the small excess of matter.

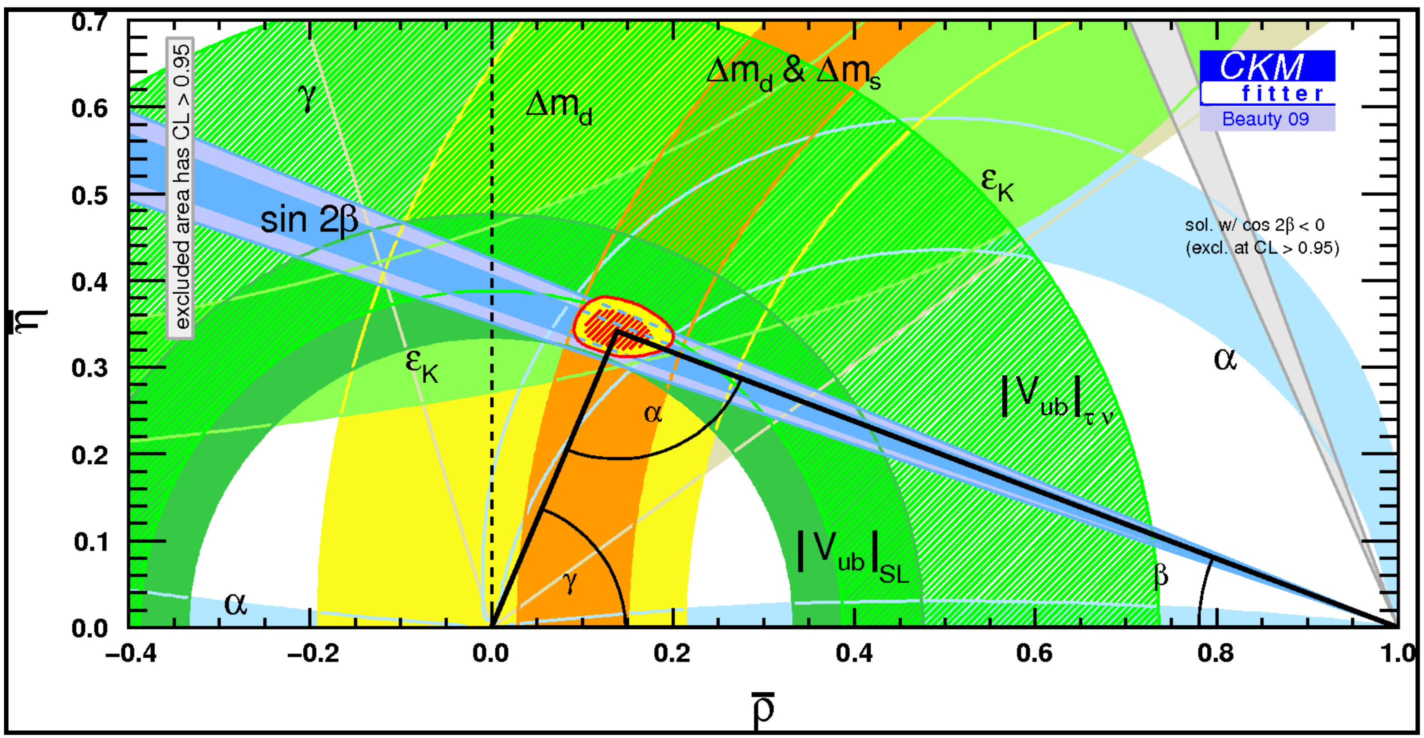


One of the three conditions (A. Sakharov) required to explain this process – **properties of particles and antiparticles must be different** (*CP* violation)

CP Violation in the Standard Model

- *CP* violation is naturally included in the standard model through the quark mixing (CKM) matrix
- Many different measurements of *CP* violation phenomena are in excellent agreement with the SM:

All measurements are consistent with a single apex of this unitarity triangle plot:



CP Violation in the Standard Model

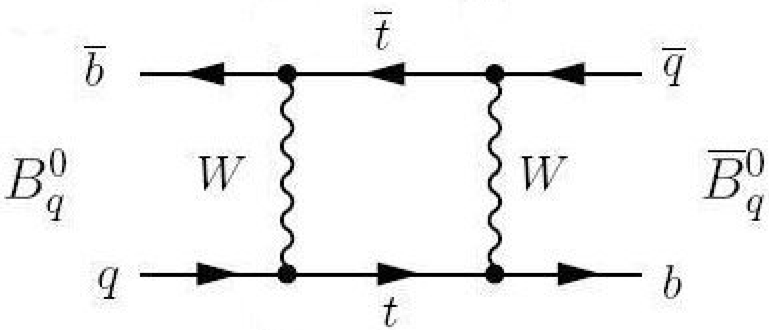
- The SM disagrees with one experimental fact – our existence!
  - The SM source of *CP* violation is not sufficient to explain the imbalance between matter and antimatter §;
  - Some theoretical studies claim up to 10 orders of magnitude deficit of the CP violation provided by the SM;
- New sources of *CP* violation are required to explain the matter dominance.

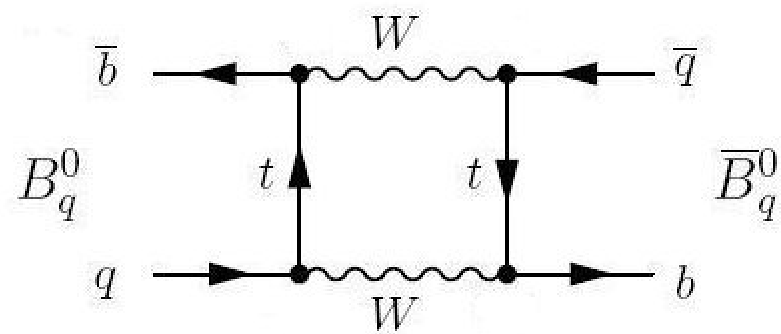
The search for new sources of *CP* violation is an important task of current and future experiments

§: e.g. P. Huet, E. Sather, Phys. Rev. D51, 379-394 (1995)

CP Violation in B Meson Mixing

- The main goal of our measurement is to study ***CP* violation in mixing** in the B^0_d and B^0_s systems;





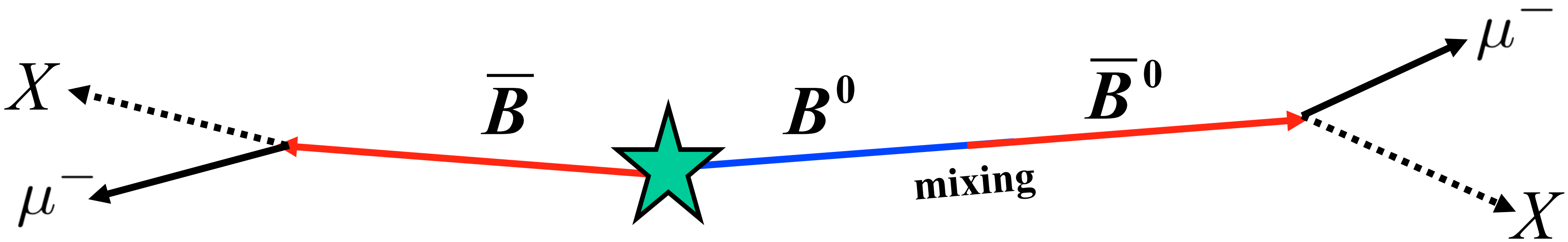
- Magnitude of this *CP* violation predicted by SM is negligible compared to present experimental sensitivity;
- Contribution of new physics can result in a significant modification of the SM prediction, which can be tested experimentally

A measurement of *CP* violation significantly different from zero would be **unambiguous** evidence of new physics

Dimuon Charge Asymmetry

We measure *CP* violation in mixing using the dimuon charge asymmetry of semileptonic *B* decays:

$$A_{sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$



One muon comes from direct semileptonic decay $\boldsymbol{b \to \mu^- X}$

Second muon comes from direct semileptonic decay after neutral *B* meson mixing: $\boldsymbol{B^0 \to \bar{B}^0 \to \mu^- X}$

i.e. N_b^{++}, N_b^{--} are the number of events with two *b* hadrons decaying semileptonically and producing **two muons of the same charge.**

Semileptonic Charge Asymmetry

Because any asymmetry arises from meson mixing, A^b_{sl} is equal to the charge asymmetry a^b_{sl} of "wrong sign" semileptonic B decays:

$$a^b_{sl} \equiv \frac{\Gamma(\bar{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\bar{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A^b_{sl}$$

"Right sign" decay is $B \to \mu^+ X$

"Wrong sign" decays can happen only due to mixing in B_d and B_s systems

This asymmetry can also be defined separately for B_d and B_s :

$$a^q_{sl} \equiv \frac{\Gamma(\bar{B}_q \to \mu^+ X) - \Gamma(B_q \to \mu^- X)}{\Gamma(\bar{B}_q \to \mu^+ X) + \Gamma(B_q \to \mu^- X)} \qquad q = d,s$$

Y. Grossman, Y. Nir, G. Raz, PRL 97, 151801 (2006)

A^b_{sl} at the Tevatron

Since both B^0_d and B^0_s are produced at the Tevatron, both a^d_{sl} and a^s_{sl} contribute linearly to A^b_{sl}:

$$A^b_{sl} = (0.506 \pm 0.043)a^d_{sl} + (0.494 \pm 0.043)a^s_{sl}$$

Unlike experiments at B factories, the Tevatron allows the charge asymmetry of both B^0_d and B^0_s mesons to be measured.

Any non-zero value of A^b_{sl} implies CPV, quantified by the phase φ_q of the B^0_q (q=d,s) mass matrix:

$$a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan(\varphi_q)$$

A^b_{sl} and the Standard Model

The Standard Model predicts a very small value of A^b_{sl}:

$$A^b_{sl} = (-0.023^{+0.005}_{-0.006})\ \%$$

New physics contribution can significantly change this value by changing the CP violating phases φ_d and φ_s

Our goal is to measure A^b_{sl} and compare it with the standard model prediction

A. Lenz, U. Nierste, hep-ph/0612167

Introduction and Theory

Analysis Overview

Measurement Details

Results

Interpretation

Experimental Observables

Experimentally, we measure two quantities...

1) Like-sign dimuon charge asymmetry:

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

2) Inclusive muon charge asymmetry:

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}}$$

$n^{+(-)}$ = total number of muons with charge +1 (-1)

Semileptonic B decays contribute to both A and a – both quantities can be used to extract A^{b}_{sl}.

Extracting A^b_{sl}

Both A and a linearly depend on the charge asymmetry A^b_{sl}

$$a = kA^b_{sl} + a_{bkg}$$

$$A = KA^b_{sl} + A_{bkg}$$

(recall that $A^b_{\text{sl}} = a^b_{\text{sl}}$)

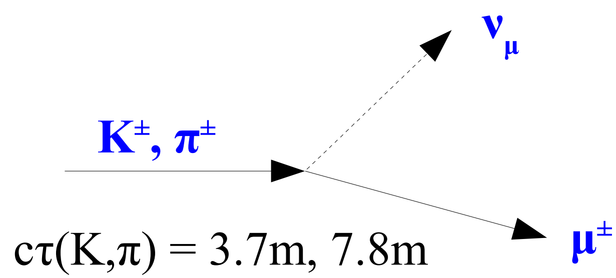
- A_{bkg} and a_{bkg} are detector-related background contributions to the measured asymmetry;
- Coefficients K and k are small (< 1) due to the effect of charge symmetric background processes diluting the semileptonic asymmetry.

Our task is to:

1) Determine the background contributions A_{bkg} and a_{bkg};
2) Find the coefficients K and k;
3) Extract the asymmetry A^b_{sl}.

Background Contribution

$$a = kA^b_{sl} + a_{bkg}$$
$$A = KA^b_{sl} + A_{bkg}$$



Sources of background muons:

- Kaon and pion decays $K^+\to\mu^+\nu$, $\pi^+\to\mu^+\nu$ or 'punch-through';
- Proton punch-through;
- Asymmetry in tracks falsely associated with muons;
- Muon reconstruction asymmetry.

We measure all background contributions directly in data, with a reduced input from simulation;

With this approach we expect to control and decrease the systematic uncertainties.

Minimizing A^{b}_{sl} Uncertainty

- The same background processes contribute to both A_{bkg} and a_{bkg};
- Therefore, the uncertainties of A_{bkg} and a_{bkg} are correlated;
- We take advantage of the correlated background contributions, and obtain A^{b}_{sl} from the linear combination:

$$\boxed{A' = A - \alpha\, a}$$

Coefficient α is selected such that the total uncertainty of A^{b}_{sl} is minimized.

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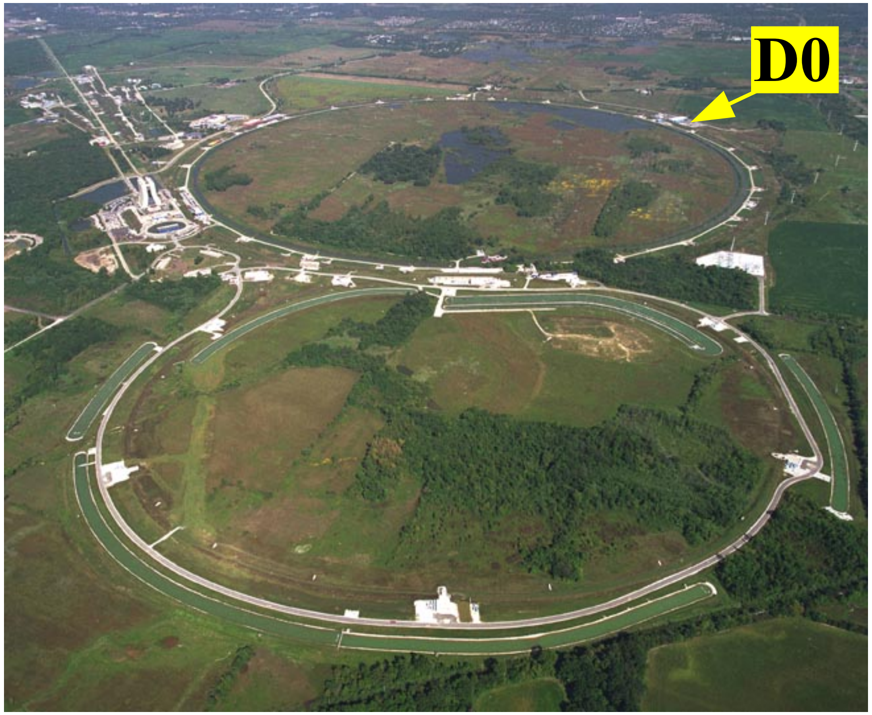
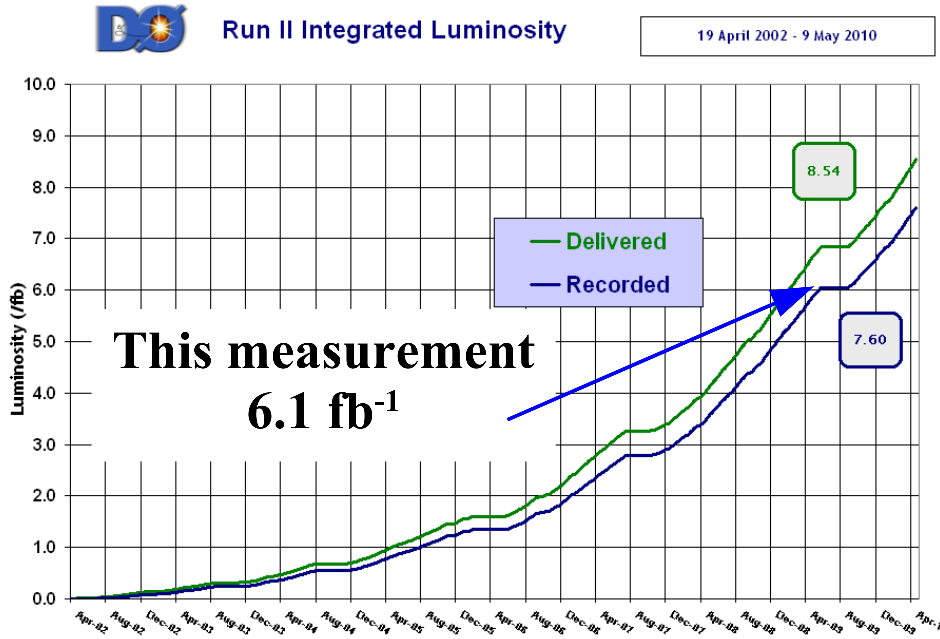
Dataset

Tevatron proton-antiproton Collider



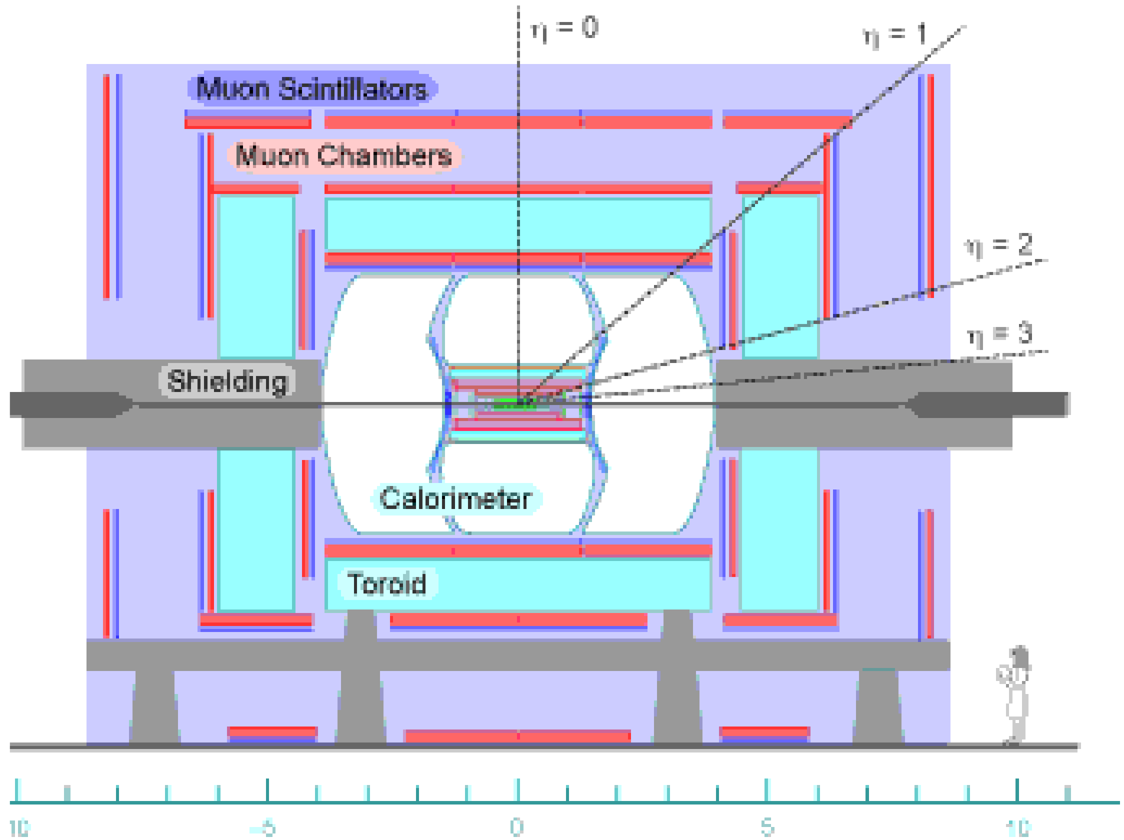


- Data collected between April 2002 and June 2009.

- Proton-antiproton initial state is (by design!) **matter-antimatter symmetric.**
- Centre-of-mass energy is 1.96 TeV.

The D0 Detector

- Inner **tracking** (silicon sensors + scintillation fibers) **within 2T solenoid magnet**;
- Combined EM/hadronic **calorimeter** minimally used in this analysis
- **Muon tracking** detector: multiple planes A-C of drift chambers on either side of **1.8T toroid magnet**.
- **Muon scintillators** provide time resolution of 2-3 ns

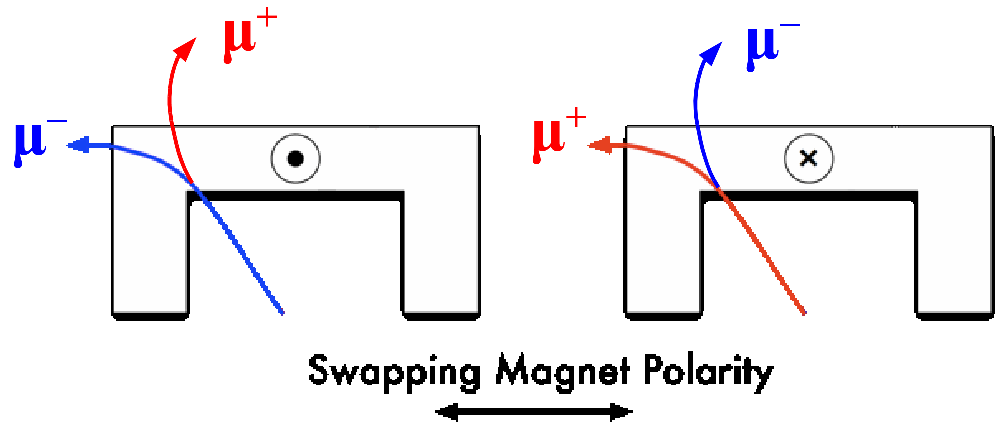


Detector is made of matter – therefore has **inherent matter-antimatter asymmetry!**

Asymmetries due to magnet polarities are mitigated by **regularly reversing currents...**

Reversal of Magnet Polarities

For a given magnet polarity, there is a charge asymmetry, e.g. from muons bending out of the muon detector acceptance;



The trajectory of a *negative* particle in a given polarity is exactly the same as the trajectory of the *positive* particle with the magnet polarity reversed;

By separately analyzing four samples corresponding to the different solenoid/toroid polarities (++, −−, +−, −+) the overall difference in the reconstruction efficiency between positive and negative particles is minimized.

Changing polarities is an important feature of the DØ detector, which reduces significantly systematics in charge asymmetry measurements.

Event selection

Inclusive muon sample:

- Charged particle identified as a muon;
- **$1.5 < p_T < 25$ GeV**;
- muon with $p_T < 4.2$ GeV must have **$|p_Z| > 6.4$ GeV**;
- pseudorapidity **$|\eta| < 2.2$**;
- Distance to primary vertex: < 3 mm in transverse plane; < 5 mm along the beam;

Like-sign dimuon sample:

- Two muons of the same charge;
- Both muons satisfy all above conditions;
- Primary vertex is common for both muons;
- Invariant mass ***$M(\mu\mu)$*** **> 2.8 GeV** to suppress events with two muons from the same *B* decay.

Blinded analysis

The central value of A^b_{sl} was extracted from the full data set only after the analysis method and all statistical and systematic uncertainties had been finalized.

Now Closing...

Raw asymmetries

$$a = kA^b_{sl} + a_{bkg}$$

$$A = KA^b_{sl} + A_{bkg}$$

By simple event counting, the raw asymmetries are:

$$\mathbf{a} \equiv \frac{\mathbf{n}^+ - \mathbf{n}^-}{\mathbf{n}^+ + \mathbf{n}^-} = (+0.955 \pm 0.003)\ \%$$

$$\mathbf{A} \equiv \frac{\mathbf{N}^{++} - \mathbf{N}^{--}}{\mathbf{N}^{++} + \mathbf{N}^{--}} = (+0.564 \pm 0.053)\ \%$$

- The inclusive muon sample contains 1.495×10^9 muons
- The like-sign dimuon sample contains 3.731×10^6 events

Background Contributions

$$a = kA^b_{sl} + a_{bkg}$$
$$A = KA^b_{sl} + A_{bkg}$$

Several background processes contribute to a_{bkg} and A_{bkg}:

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

Total 'fraction' of muons in each **dimuon** event is 2

- f_K, f_π, and f_p are the fractions of kaons, pions and protons identified as a muon in the inclusive muon sample;
- a_K, a_π, and a_p are the charge asymmetries of kaon, pion, and proton tracks;
- δ is the charge asymmetry of muon reconstruction;
- $f_{bkg} = f_K + f_\pi + f_p$

Uppercase variables are the same quantities defined in the **same-sign dimuon sample**

Kaon Detection Asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- The largest background asymmetry comes from the charge asymmetry of kaon tracks identified as muons **(a_K, A_K)**;
- Interaction cross section of K^+ and K^- with the detector material is different, especially for kaons with low momentum:

  @ $p(K)$ = 1 GeV: $\sigma(K^- d) \approx 80$ mb $\sigma(K^+ d) \approx 33$ mb

  This is because the reaction $K^- N \rightarrow Y\pi$ has no $K^+ N$ analogue;
- Hence K^+ mesons travel further in the detector on average, having a greater probability of decaying to muons, or punching through to the muon system – **the asymmetries a_K and A_K should be positive**.

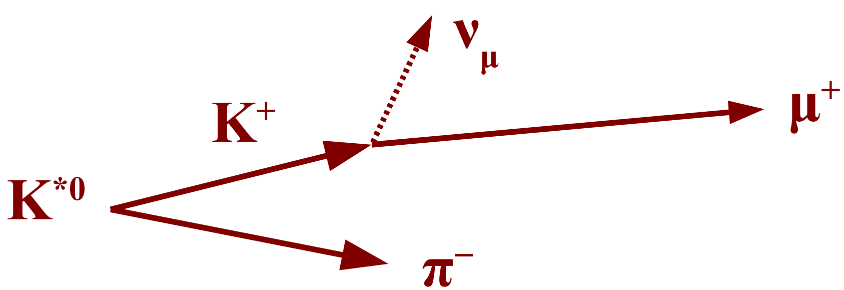
Measuring Kaon Asymmetry

Starting from the inclusive muon sample...

1) Define sources of kaons from resonances which can be fitted to extract signal size (two independent samples):

$$K^{*0} \rightarrow K^+\pi^- \qquad\qquad \varphi(1020) \rightarrow K^+K^-$$

2) Require that the kaon is identified as a muon, e.g.:

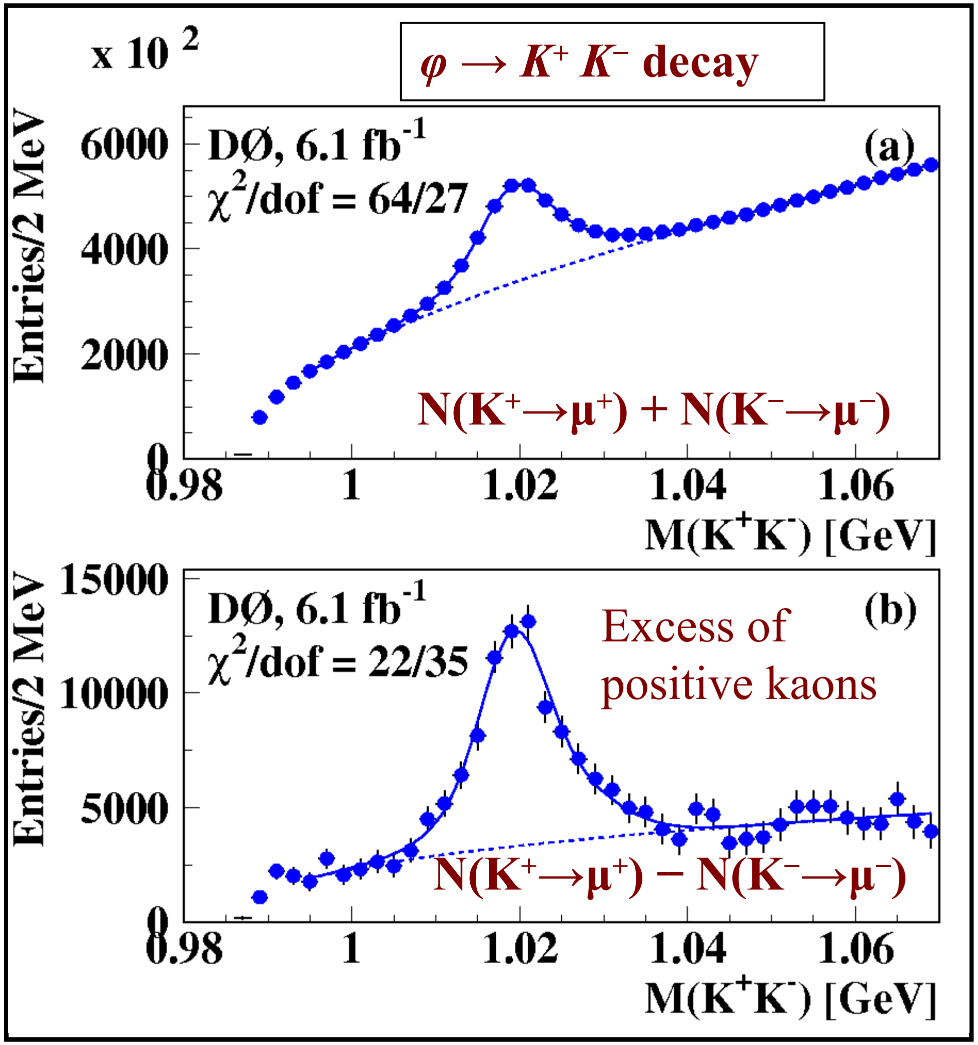


kaon usually decays outside tracking detector – so momentum is correctly measured.

3) Build the mass distribution separately for positive and negative kaons;

4) Compute asymmetry in the number of observed events;

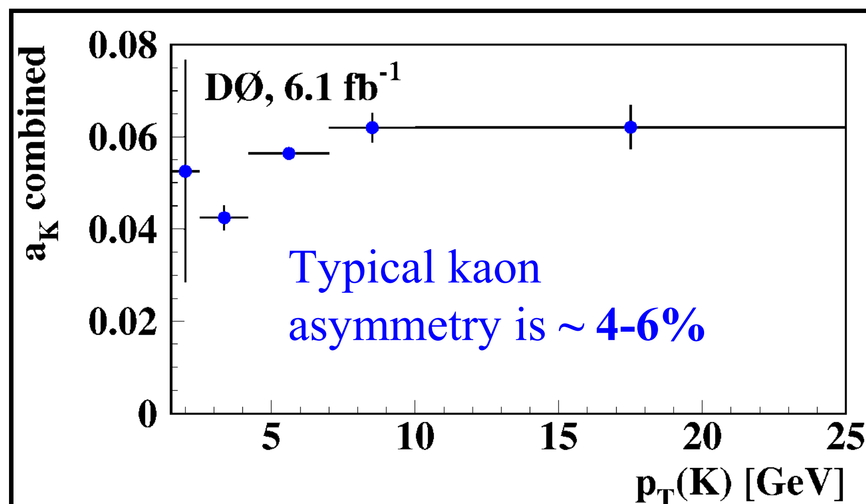
Measuring Kaon Asymmetry



For each channel, K^{*0} and φ(1020), the asymmetry is determined is bins of kaon transverse momentum.

The results for both channels agree (χ^2 of difference is 5.4/5 degrees-of-freedom), so they are combined to produce $\mathbf{a_K}$.

The same-sign dimuon asymmetry $\mathbf{A_K}$ is then determined algebraically from a_K, based on the two p_T values of the muons.



Pion and Proton Asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

The same strategy is used to determine a_π , a_p , A_π and A_p.

- $K_S \rightarrow \pi^+ \pi^-$ is used to measure pion asymmetry;
- $\Lambda \rightarrow p\, \pi^-$ is used to measure proton asymmetry.

a_K	a_π	a_p
$(+5.51 \pm 0.11)\%$	$+(0.25 \pm 0.10)\%$	$(+2.3 \pm 2.8)\%$

In fitting with expectations, the kaon asymmetry is positive, and forms the largest contribution.

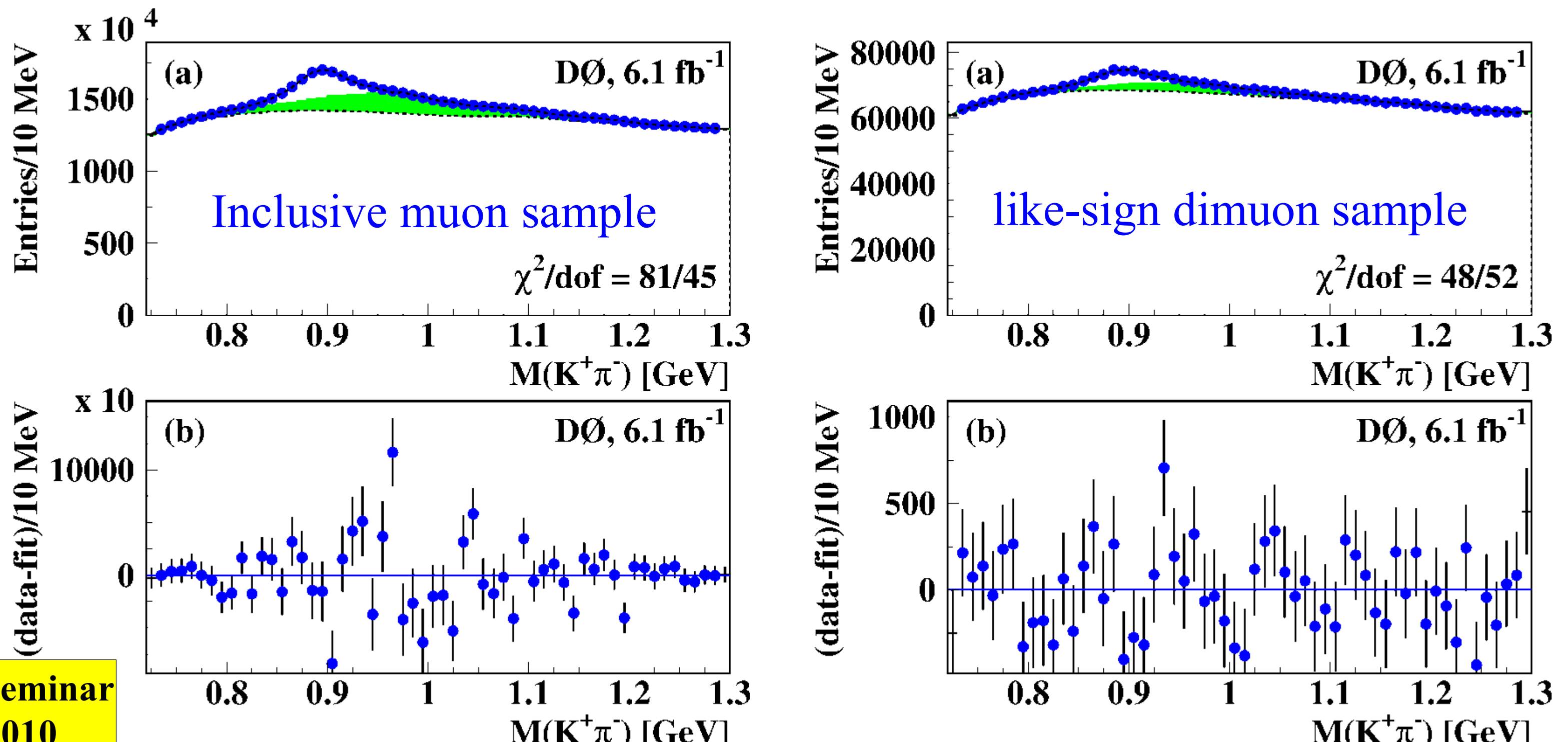
Sample Composition: f_K, F_K

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

Fractions f_K , F_K are measured in a two-stage process:

1) Measure $f_{K^{*0}}$, $F_{K^{*0}}$ by fitting the mass distribution of $K^{*0} \to K^+\pi^-$

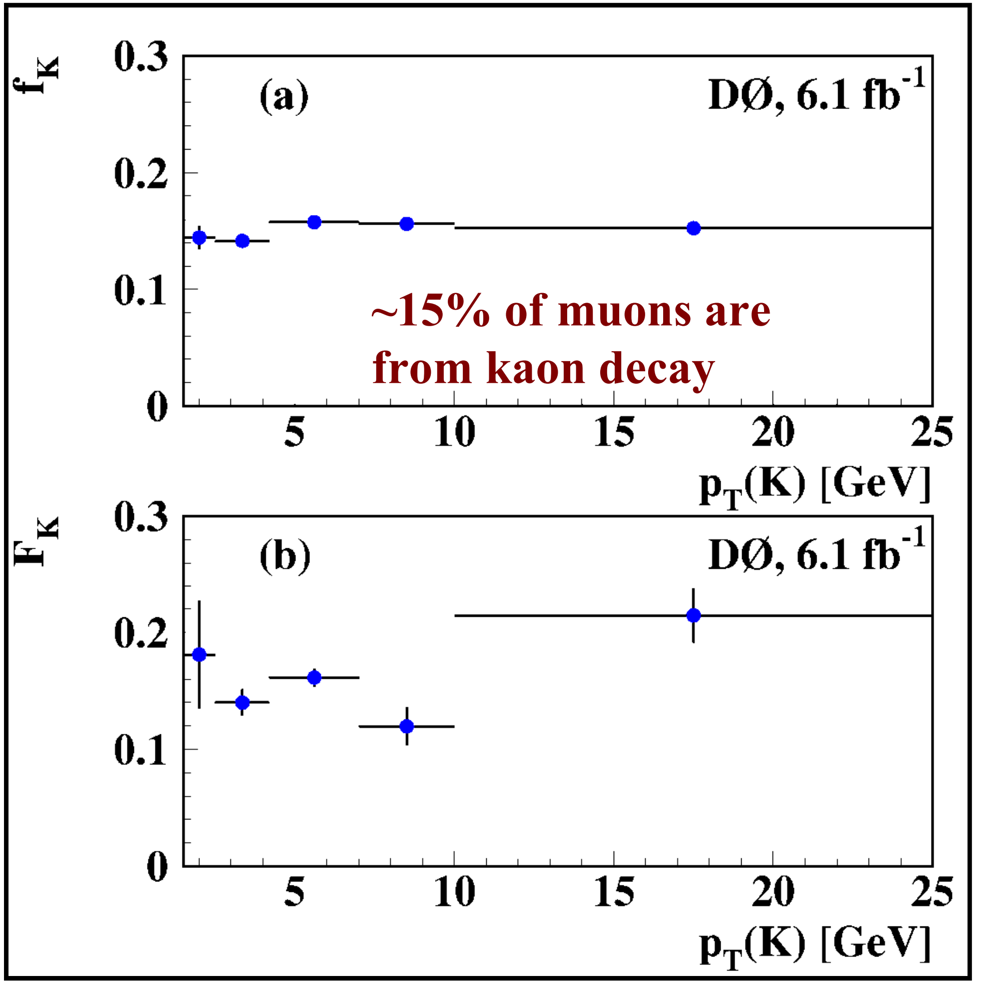


Sample Composition: f_K, F_K

2) Convert to f_K , F_K using the fraction $f_{K^{*0}}/f_K$ measured by comparing with the similar decay $K^{*+} \to K_S \pi^-$

$$f_K = \frac{N(K_S)}{N(K^{*+})} f_{K^{*0}}$$

$$F_K = \frac{N(K_S)}{N(K^{*+})} F_{K^{*0}}$$



(Requires some assumptions, such as isospin invariance, and is verified in simulation – see backup slides).

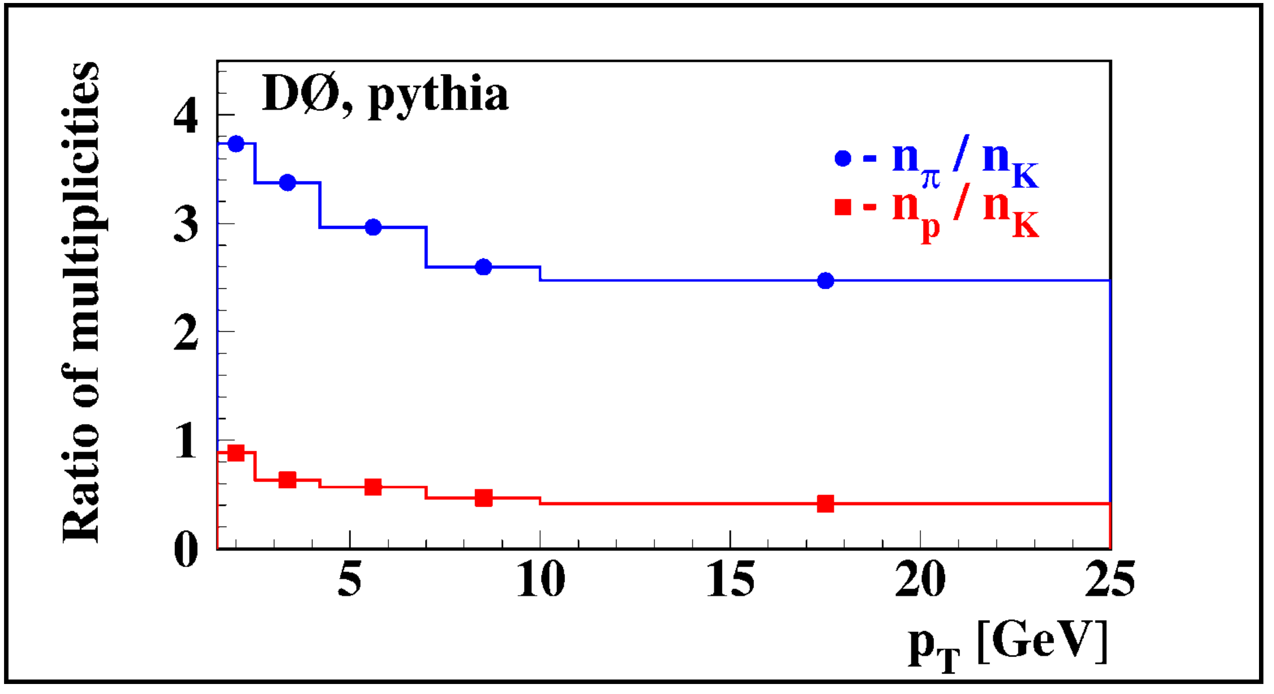
As usual, the fractions f_K and F_K are expressed in bins of kaon p_T.

Measurement of f_π , f_p , F_π , F_p

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

Fractions f_π , f_p , F_π , F_p are obtained using f_K and F_K with an additional input from simulation on the ratio of multiplicities $\mathbf{n_\pi/n_K}$ and $\mathbf{n_p/n_K}$:



Summary of Background Composition

$$\mathbf{f}_{\mathrm{bkg}} = f_K + f_\pi + f_p$$

We get the following background fractions in the inclusive muon sample:

	$(1-f_{bkg})$	f_K	f_π	f_p
MC	(59.0±0.3)%	(14.5±0.2)%	(25.7±0.3)%	(0.8±0.1)%
Data	(58.1±1.4)%	(15.5±0.2)%	(25.9±1.4)%	(0.7±0.2)%

- Uncertainties for both data and simulation are statistical only;
- Simulation fractions are given as a cross-check only, and **are not used in the analysis**;
- Good agreement is found between data and simulation, within the systematic uncertainties assigned;
- Fractions for same-sign dimuon sample are extracted similarly.

Muon Reconstruction Asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

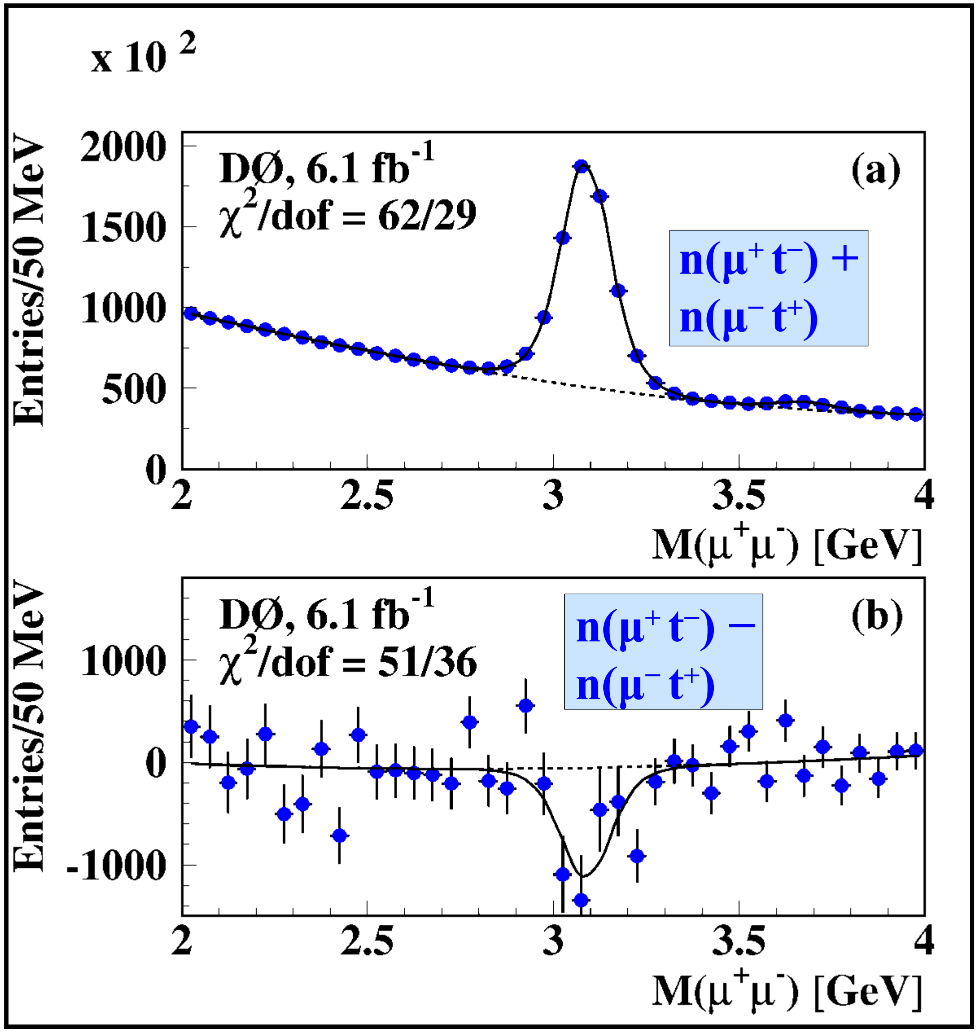
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

Final piece of the equation needed to determine a_{bkg} and A_{bkg};

- Reversal of toroid and solenoid polarities cancels 1st-order detector effects;
- Quadratic terms in detector asymmetries still can contribute into the muon reconstruction asymmetry;
- Detector asymmetries for a given magnet polarity $a_{det} \approx O(1\%)$;
- Therefore, we can expect the residual reconstruction asymmetry :

$$\delta \approx \Delta \approx O\ (0.01\%)$$

Muon Reconstruction Asymmetry



We measure the muon reconstruction asymmetry using $J/\psi \to \mu\mu$ events, where a muon is combined with any track of opposite charge:

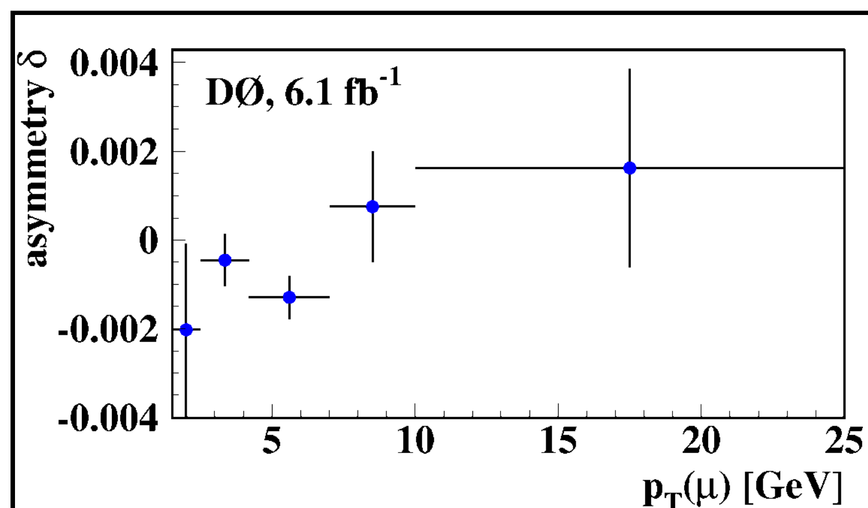
$$\delta = (-\ 0.076 \pm 0.028)\ \%$$

$$\Delta = (-\ 0.068 \pm 0.023)\ \%$$

To be compared with:

$$a = (+\ 0.955 \pm 0.003)\ \%$$

$$A = (+\ 0.564 \pm 0.053)\ \%$$



Summary of Background Contributions

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

We obtain:

	$f_K a_K$ (%) or $F_K A_K$ (%)	$f_\pi a_\pi$ (%) or $F_\pi A_\pi$ (%)	$f_p a_p$ (%) or $F_p A_p$ (%)	$(1-f_{bkg})\delta$ (%) or $(2-F_{bkg})\Delta$ (%)	a_{bkg} or A_{bkg}
Inclusive	0.854 ± 0.018	0.095 ± 0.027	0.012 ± 0.022	-0.044 ± 0.016	0.917 ± 0.045
Dimuon	0.828 ± 0.035	0.095 ± 0.025	0.000 ± 0.021	-0.108 ± 0.037	0.815 ± 0.070

- All uncertainties are statistical only;
- Notice that background contribution is similar for inclusive muon and dimuon sample: $A_{bkg} \approx a_{bkg}$

Signal Contribution

After subtracting the background contribution from the raw asymmetries a and A, the remaining residual asymmetries are proportional to A^b_{sl}:

$$a = kA^b_{sl} + a_{bkg} \qquad \longrightarrow \qquad a - a_{bkg} = kA^b_{sl}$$

$$A = KA^b_{sl} + A_{bkg} \qquad \longrightarrow \qquad A - A_{bkg} = KA^b_{sl}$$

- The factors k and K account for 'signal' events (real muons) from sources which are fully symmetric, and only contribute to the denominator in A^b_{sl}.
- In addition to the oscillation process $\mathbf{\bar{B}_q^0 \rightarrow B_q^0 \rightarrow \mu^+ X}$, several other decays of b- and c-quark contribute to the inclusive muon and like-sign dimuon samples
- Monte Carlo simulation is used to measure the effect of these decays, and extract the coefficients ***k*** and ***K***.

Coefficients k and K

$$a - a_{bkg} = k A^b_{sl}$$
$$A - A_{bkg} = K A^b_{sl}$$

Decays contributing to the muon sample include:

- $b \rightarrow \mu^- X$ (including possible oscillations)
- $b \rightarrow c \rightarrow \mu^+ X$ (including possible oscillations)
- $b \rightarrow c\bar{c}q$
- $c\bar{c}$ and $b\bar{b}c\bar{c}$ production
- η, ω, ρ^0, $\varphi(1020)$, J/ψ, ψ' decaying to $\mu^+\mu^-$

These decays are currently measured with a good precision (see PDG), and this input from simulation produces a small systematic uncertainty.

$$k = 0.041 \pm 0.003$$
$$K = 0.342 \pm 0.023$$

k is found to be much smaller than *K*, because many more non-oscillating *b*- and *c*-quark decays contribute to the inclusive asymmetry.

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Bringing Everything Together

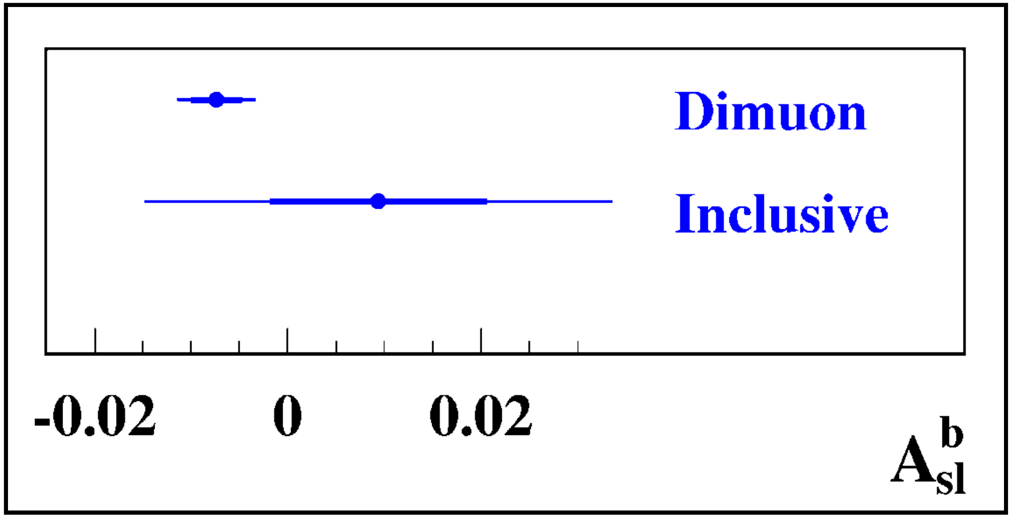
Using all results on background and signal contributions we get two separate measurements of A^b_{sl} from inclusive and like-sign dimuon samples:

From ***a***: $A^b_{sl} = [\ +0.94 \pm 1.12\ \text{(stat.)} \pm 2.14\ \text{(syst.)}\ ]\ \%$

From ***A***: $A^b_{sl} = [\ -0.736 \pm 0.266\ \text{(stat.)} \pm 0.305\ \text{(syst.)}\ ]\ \%$

Uncertainties of the first result are much larger, because of a small coefficient $k = 0.041 \pm 0.003$

Dominant contribution into the systematic uncertainty comes from the measurement of f_K and F_K fractions.

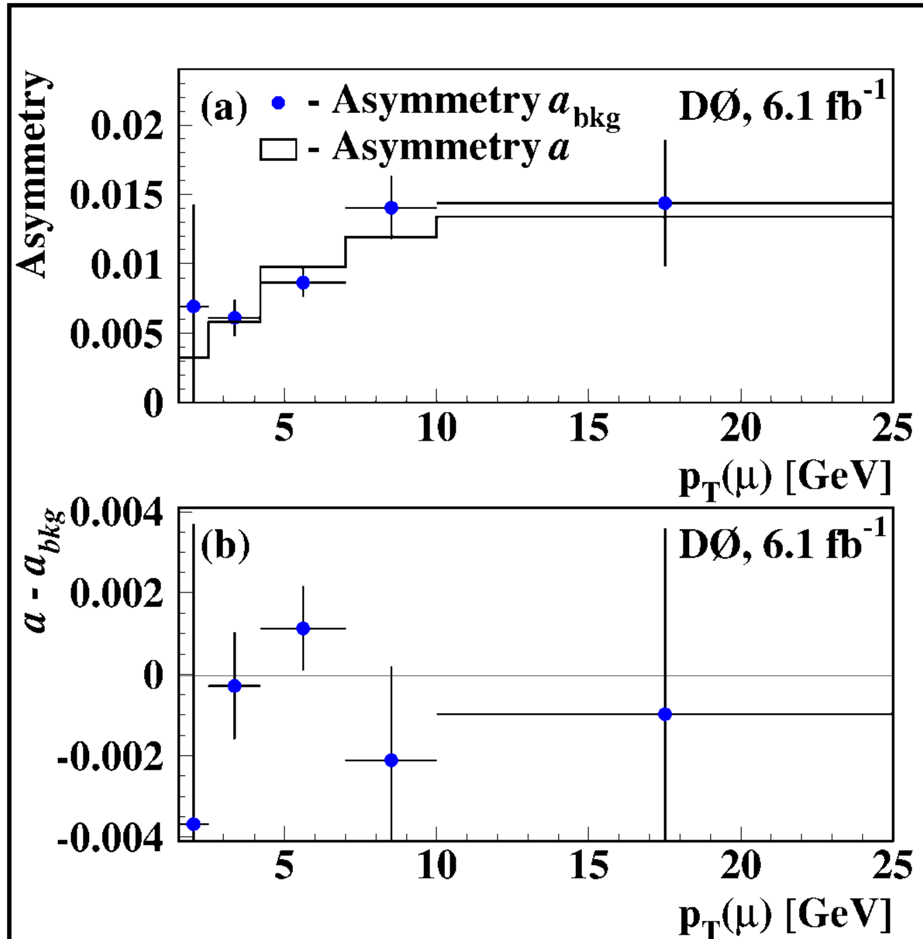


Closure Test

- The contribution of A^b_{sl} in the inclusive muon asymmetry a is suppressed by:

  $$k = 0.041 \pm 0.003;$$

- The value of a is mainly determined by the background asymmetry a_{bkg};
- We measure a_{bkg} in data, and we can verify how well it describes the observed asymmetry a;
- We compare a and a_{bkg} as a function of muon p_T ;
- We get χ^2/d.o.f. = 2.4/5 for the difference between these two distributions;



Excellent agreement between the expected and observed values of a , including a p_T dependence

Combining Measurements

- Many uncertainties in these two measurements are correlated;
- We obtain the final result using the linear combination:

$$\mathbf{A' \equiv A - \alpha \cdot a = (K - \alpha \cdot k) A^{b}_{sl} + (A_{bkg} - \alpha \cdot a_{bkg})}$$

where the parameter α is selected such that the total uncertainty of A^b_{sl} is minimized;

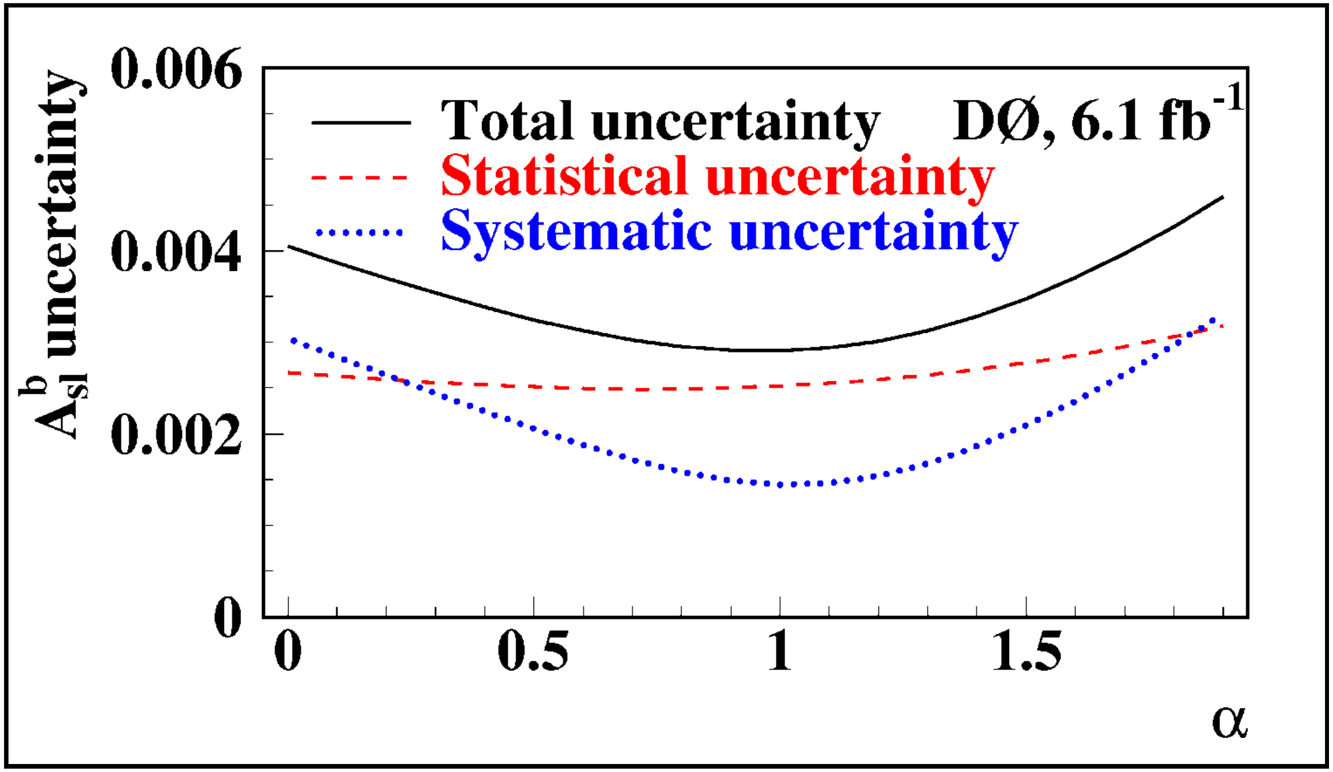
- Since $\boldsymbol{A_{bkg} \approx a_{bkg}}$ and the uncertainties of these quantities are correlated, we can expect the cancellation of background uncertainties in A' for $\boldsymbol{\alpha \approx 1}$
- The signal asymmetry $\boldsymbol{A^b_{sl}}$ does not cancel in A' for $\alpha \approx 1$ because:

$$\mathbf{k << K}$$

Combining Measurements

Optimal value of α is obtained by the scan of the total uncertainty of A^b_{sl} obtained from A'

- The value $\boldsymbol{\alpha}$ **= 0.959** is selected:



Final Result...

Final Result

- From $\boldsymbol{A' = A - \alpha}$ a we obtain a value of $A^b{}_{sl}$:

$$\mathbf{A^b{}_{sl} = [\, -\, 0.957 \pm 0.251\ (stat.) \pm 0.146\ (syst.)\,]\ \%}$$

- To be compared with the SM prediction:

$$\mathbf{A^b{}_{sl}\ (SM) = [\, -\, 0.023\,^{+0.005}_{-0.006}]\ \%}$$

- This result differs from the SM prediction by **~3.2 σ**

Statistical and Systematic Uncertainties

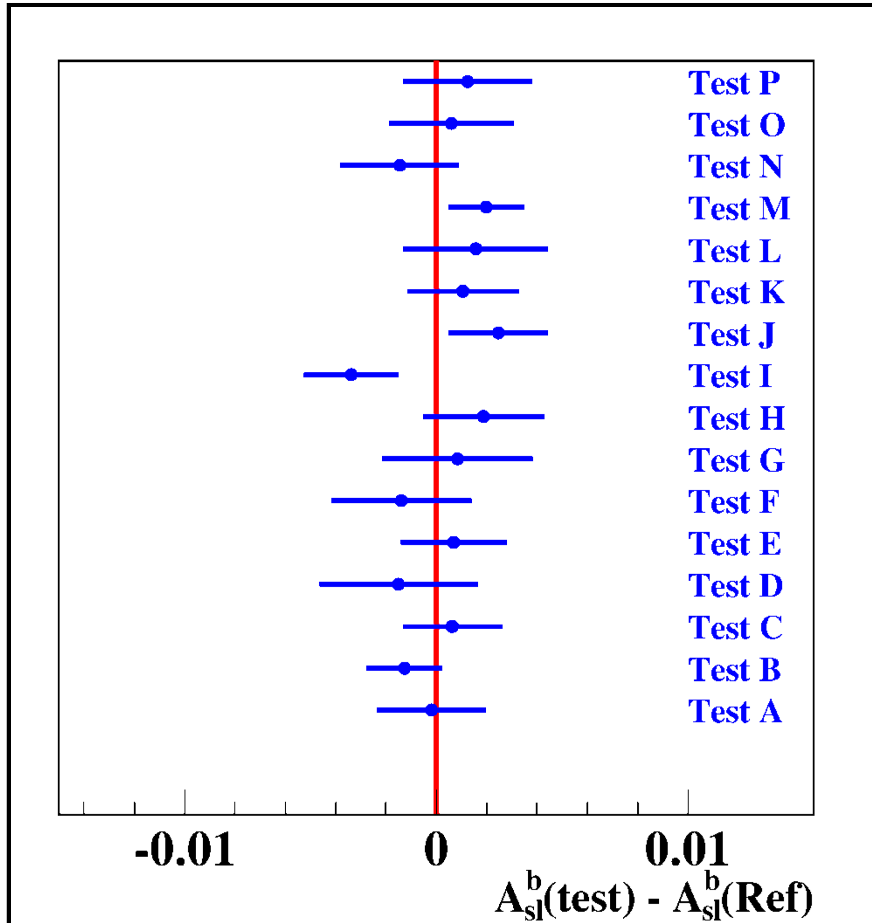
Source	A^b_{sl} *Inclusive*	A^b_{sl} *Dimuon*	A^b_{sl} *Combined*
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	0.02415	0.00405	0.00290

Dominant uncertainties

Dominant uncertainty changes from systematic → statistical

Consistency Tests

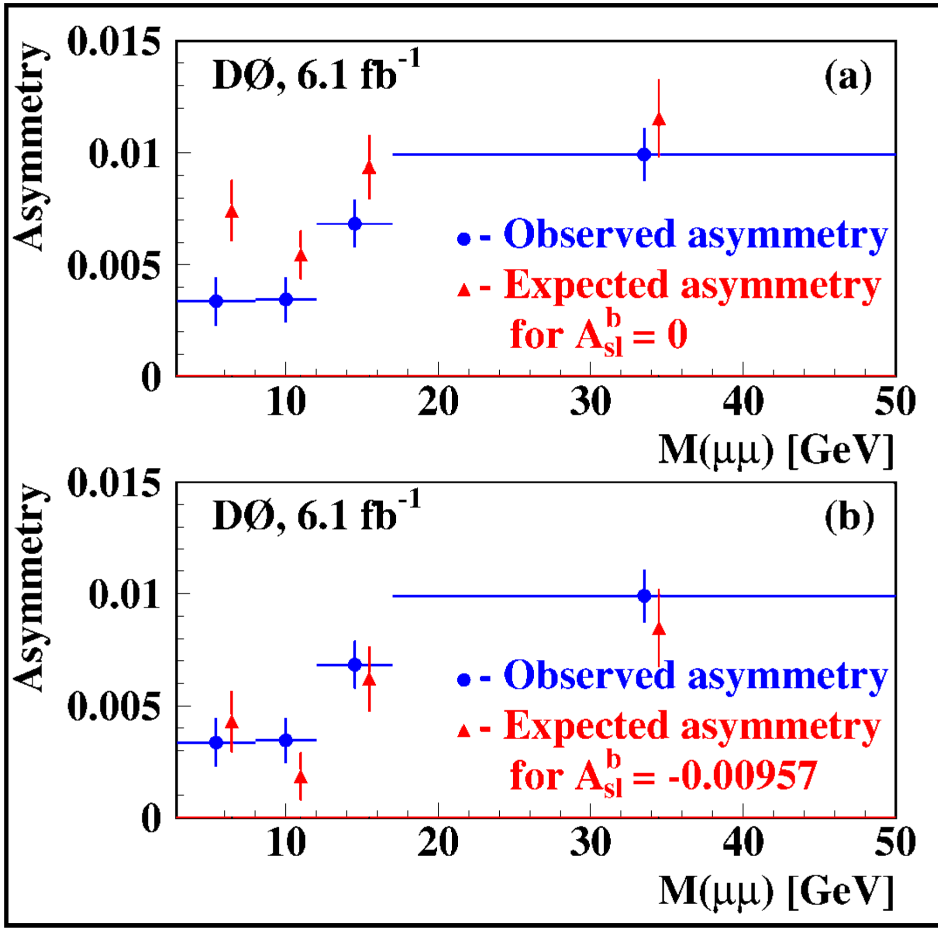
- We modify the selection criteria, or use a sub-set of the data, to test the stability of the final result;
- 16 tests in total are performed;
- There is significant variation of the raw asymmetries A and a (up to 140%) due to changes in the background composition;
- However, A^b_{sl} remains stable in all tests.



The developed method is stable and gives a consistent result after modifying selection criteria over a wide range

Dependence on Dimuon Mass

- We compare the expected and observed raw dimuon charge asymmetry A for different invariant masses $M(\mu\mu)$;
- The expected and observed asymmetries agree well for $A^b_{sl} = -0.00957$;
- Agreement is over the entire $M(\mu\mu)$ range – supports B physics as the source of anomalous asymmetry.



Dependence on the dimuon mass is well described by the analysis method.

Introduction and Theory

Analysis Overview

Measurement Details

Results

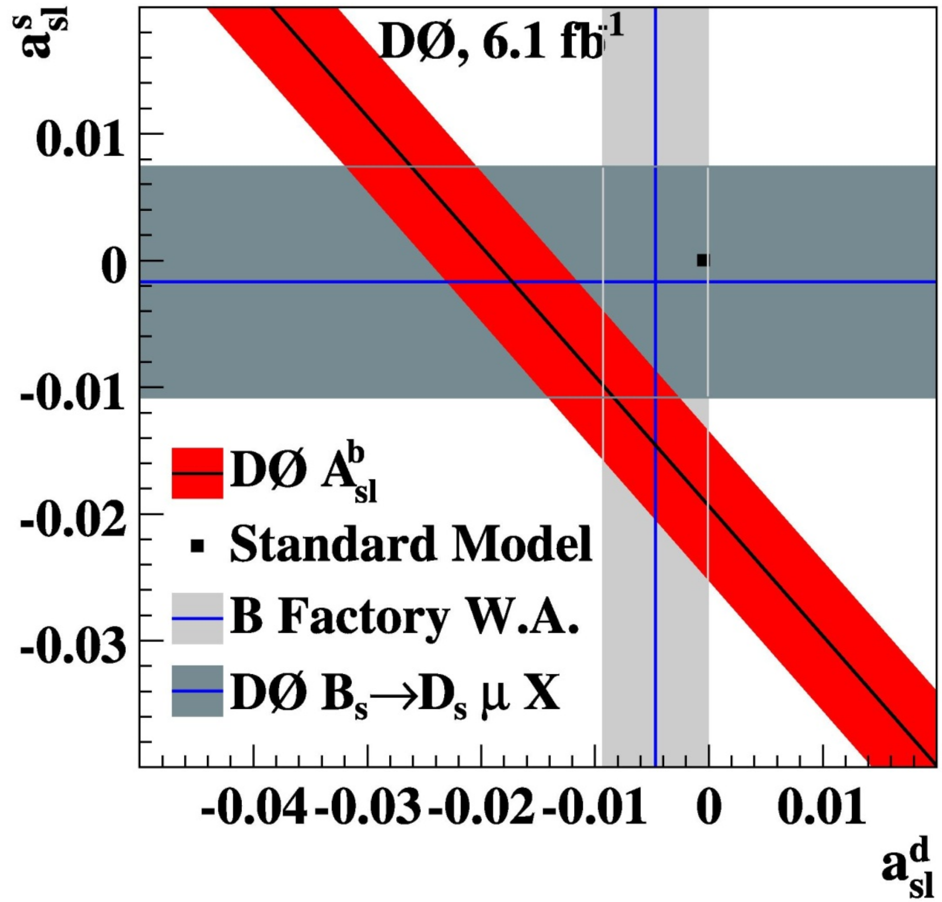
→ ***Interpretation*** ←

Comparison with Other Measurements

- In this analysis we measure a linear combination of a^d_{sl} and a^s_{sl}:

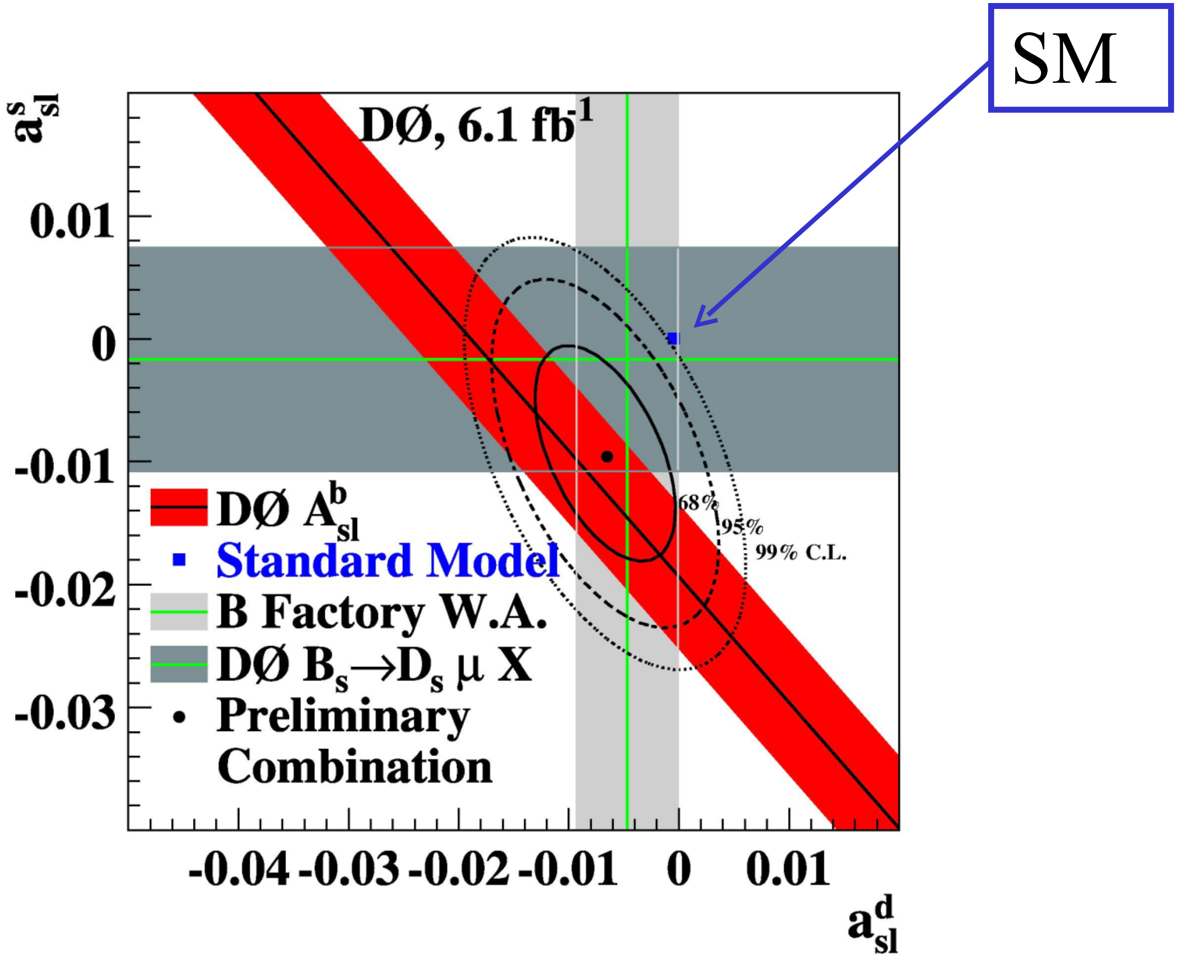
$$A^b_{sl} = 0.506\, a^d_{sl} + 0.494\, a^s_{sl}$$

- Obtained result agrees well with other measurements of a^d_{sl} and a^s_{sl}



Preliminary Combination

Our (preliminary) combination of all measurements of semileptonic charge asymmetry shows a similar deviation from the SM.



Sensitivity to a^s_{sl}

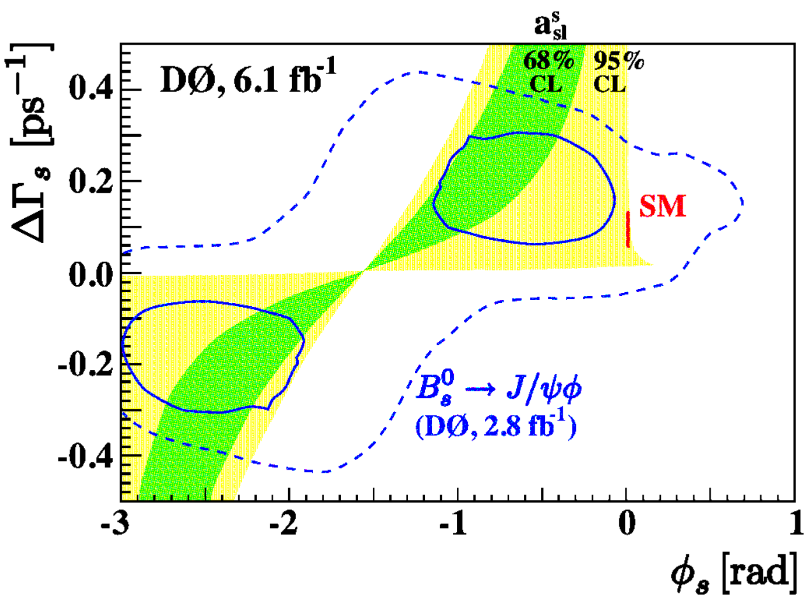
- Obtained A^b_{sl} value can be translated to the semileptonic charge asymmetry of the B_s meson system;
- We need additional input of $\boldsymbol{a^d_{sl}}$ **= −0.0047±0.0046** measured at B factories;
- We obtain: $$\boxed{a^s_{sl} = (\,-1.46 \pm 0.75\,)\%}$$
- To be compared with the SM prediction:

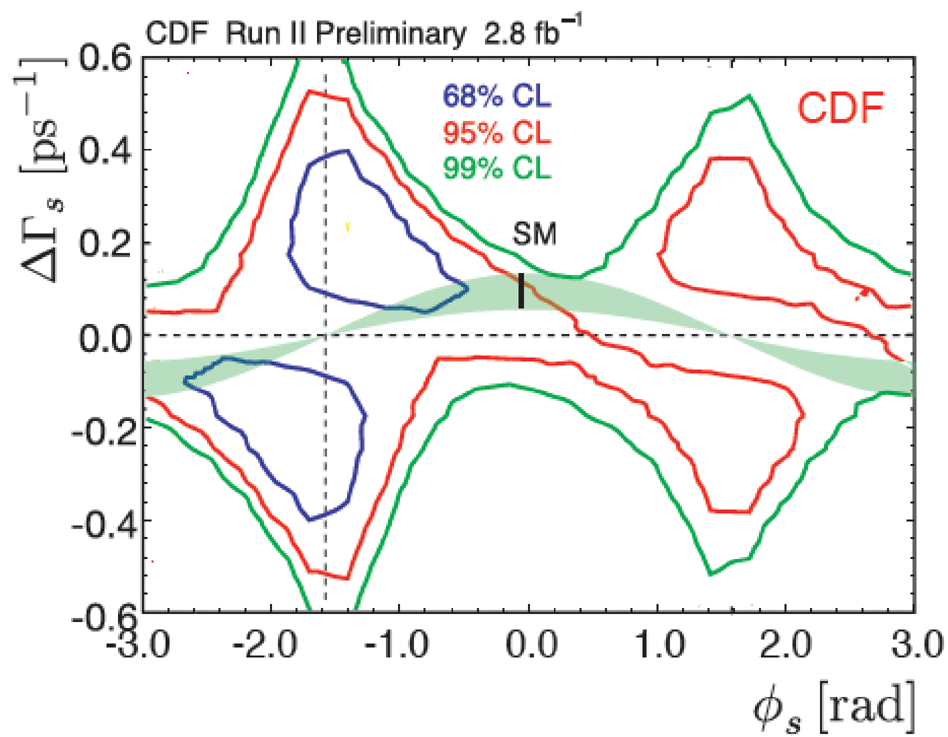
$$\boxed{a^s_{sl} = (\,+0.0021 \pm 0.0006\,)\%}$$

- Disagreement with the SM is reduced because of the additional experimental input of $\boldsymbol{a^d_{sl}}$.

Comparison with Other Measurements

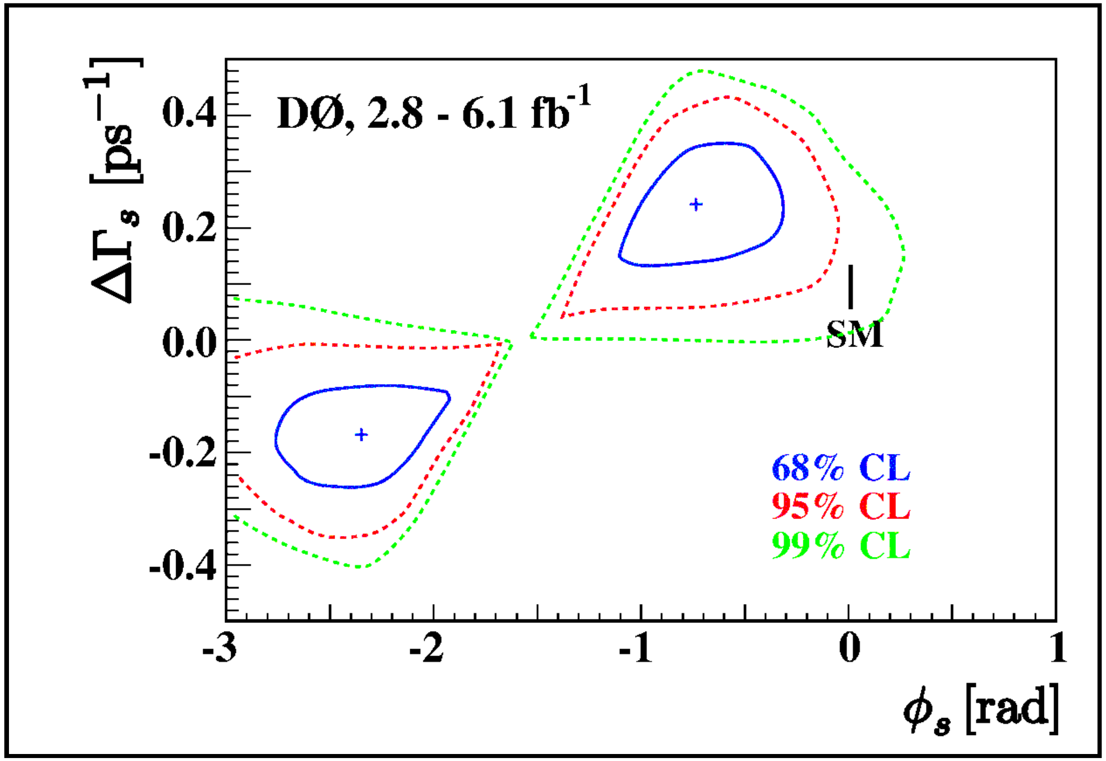
- Obtained value of a^s_{sl} can be further translated into a 2D constraint on the CP violating phase ϕ_s and $\Delta\Gamma_s$;
- The contours are in excellent agreement with independent measurements of ϕ_s and $\Delta\Gamma_s$ in $B_s \to J/\psi\phi$ decay (CDF and D0);





Combination of Results

- This measurement and the result of the DØ analysis in $B_s \rightarrow J/\psi\phi$ can be combined together;
- This combination excludes the SM value of ϕ_s at more than 95% C.L.



Result at a Glance

- Evidence of an anomalous charge asymmetry in the number of muons produced in the initially *CP* symmetric $p\bar{p}$ interaction;
- This asymmetry is inconsistent with the SM prediction at a 3.2σ level;
- This new result is consistent with other measurements;
- We observe that the number of matter particles produced (negative muons) is larger than the number of antimatter particles produced;
- Therefore, the sign of the observed asymmetry is consistent with the sign of *CP* violation required to explain the abundance of matter in our Universe;

This result may provide an important input for explaining the matter dominance in our Universe

Conclusions

- A new measurement of A^b_{sl} is performed:

$$A^b_{sl} = [\, -0.957 \pm 0.251\ (\text{stat.}) \pm 0.146\ (\text{syst.})\,]\ \%$$

- Almost all relevant quantities are obtained from data with minimal input from simulation;
- Closure test shows good agreement between expected and observed asymmetries in the inclusive muon sample;
- The dominant uncertainty is statistical – precision can be improved with more luminosity.
- The paper has now been submitted to Phys. Rev. D, and a summary paper will be submitted to Phys. Rev. Lett. *(arXiv:1005.2575)*

Backup Slides:

- *Theory and Notation;*
- *Measurement of* $\boldsymbol{f_K}$ *and* $\boldsymbol{F_K}$*;*
- *Extracting* $\boldsymbol{f_\pi}$, $\boldsymbol{F_\pi}$, $\boldsymbol{f_p}$, $\boldsymbol{F_p}$*;*
- *Muon Reconstruction Asymmetry;*
- *Track Reconstruction Asymmetry;*
- *Diluting Processes in k and K;*
- *Consistency Tests.*

A^b_{sl} and *CP* violation

A non-zero value of A^b_{sl} means that the semileptonic decays of B_q^0 and $\bar{B}_q^0$ are different;

It implies ***CP* violation in mixing**;

- This occurs only due to mixing in the B_d and B_s systems;
- i.e. meson spends more time in $\bar{B}^0_q$ state ($b\bar{s}$) than B^0_q ($\bar{b}s$);

Quantity describing *CP* violation in mixing is the complex phase ϕ_q of the B^0_q ($q = d,s$) mass matrix:

$$\|M_q\| = \begin{bmatrix} M_q & M_q^{12} \\ (M_q^{12})^* & M_q \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma_q & \Gamma_q^{12} \\ (\Gamma_q^{12})^* & \Gamma_q \end{bmatrix}$$

$$\Delta M_q = M_H - M_L \approx 2\left|M_q^{12}\right|$$

$$\Delta\Gamma_q = \Gamma_L - \Gamma_H \approx 2\left|\Gamma_q^{12}\right|\cos\phi_q$$

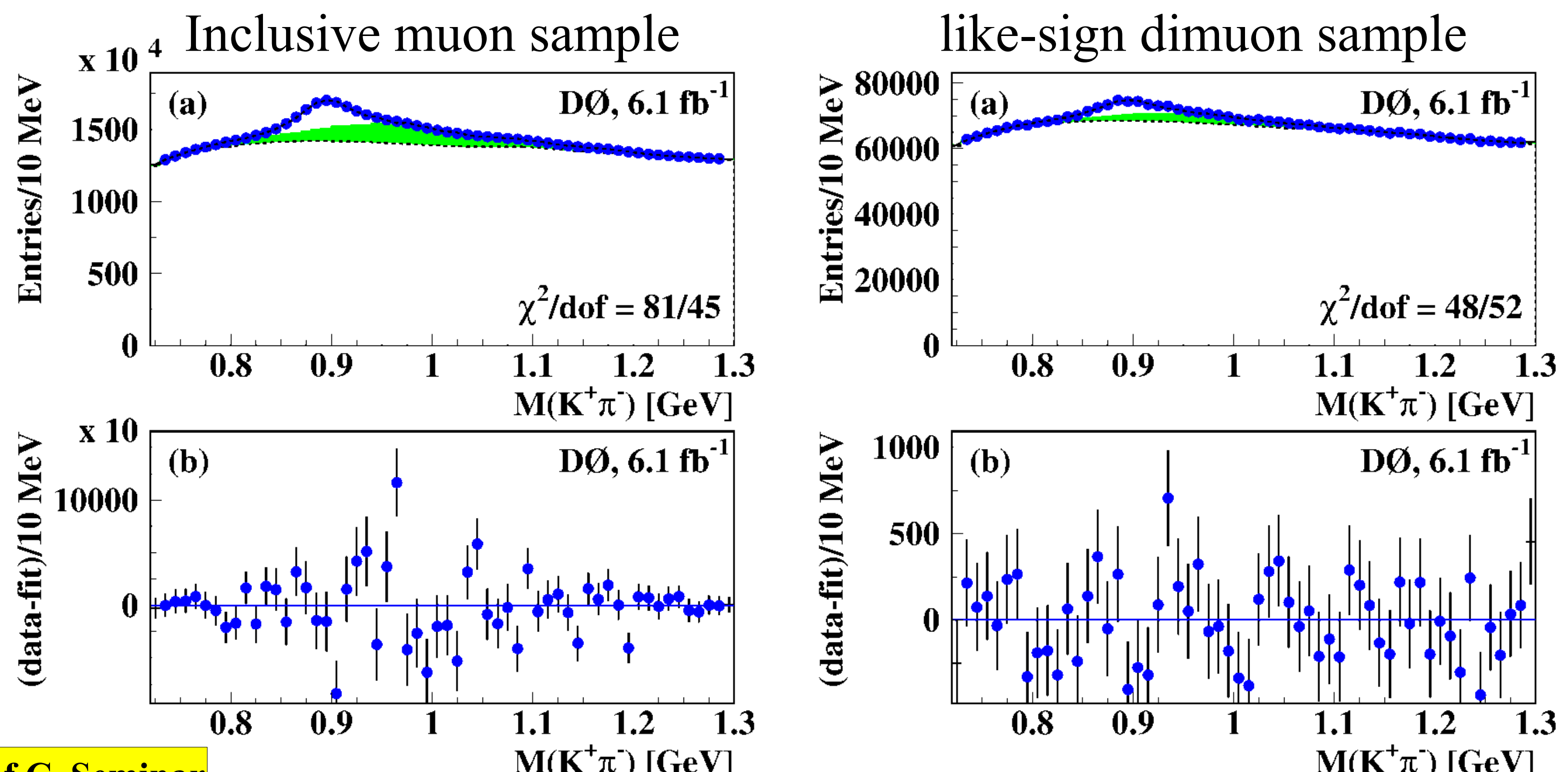
$$\phi_q = \arg\left(-\frac{M_q^{12}}{\Gamma_q^{12}}\right)$$

a^q_{sl} is related with the CP violating phase ϕ_q as:

$$a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q}\tan(\phi_q)$$

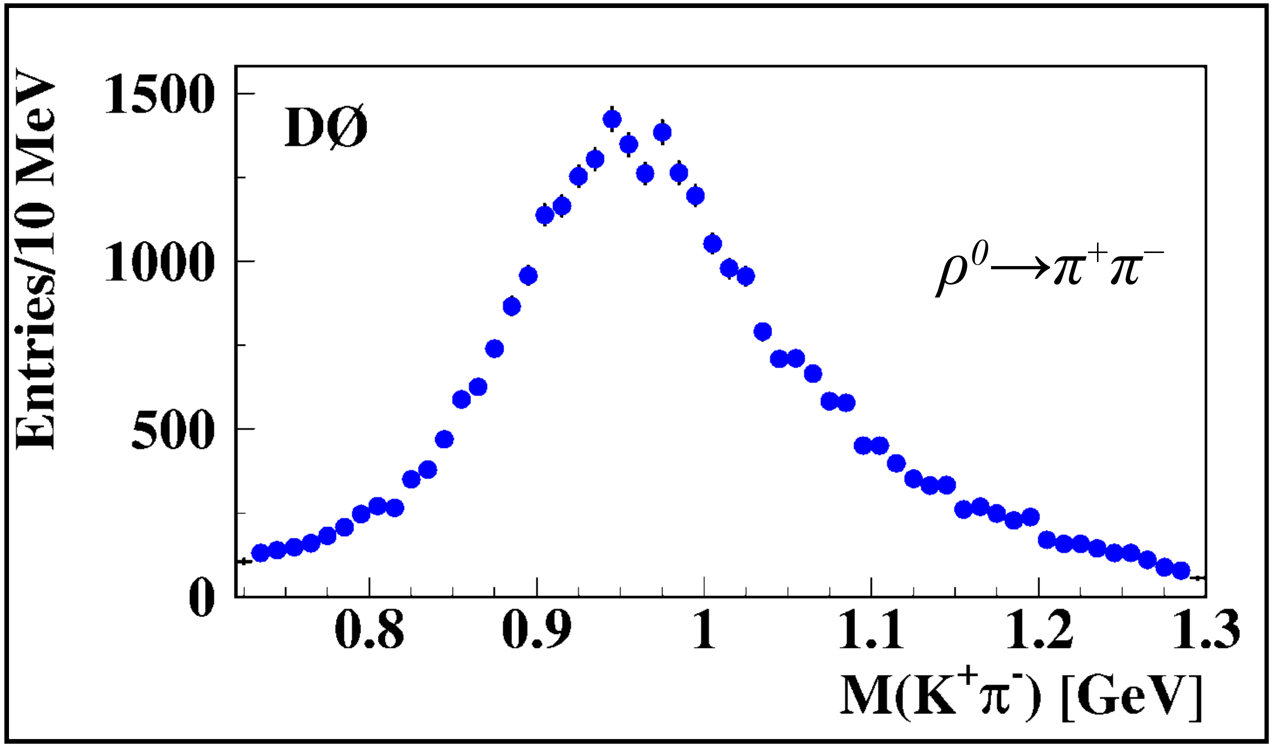
Measurement of f_K, F_K

- Fractions f_K , F_K are measured using the decays $K^{*0} \rightarrow K^+\pi^-$ selected in the inclusive muon and like-sign dimuon samples respectively;
- Kaon is required to be identified as a muon;
- We measure fractions $f_{K^{*0}}$, $F_{K^{*0}}$;



Peaking background contribution

- Decay $\rho^0 \to \pi^+\pi^-$ produces a peaking background in the (Kπ) mass, because one pion can be misidentified as a kaon;
- The mass distribution from $\rho^0 \to \pi^+\pi^-$ is taken from simulation.



Measurement of f_K, F_K

To convert these fractions to f_K , F_K, we need to know the fraction $R(K^{*0})$ of charged kaons from $K^{*0} \to K^+\pi^-$ and the efficiency to reconstruct an additional pion ε_0 :

$$f_{K^{*0}} = f_K R(K^{*0})\varepsilon_0; \quad F_{K^{*0}} = F_K R(K^{*0})\varepsilon_0$$

What we measure

What we need

Fraction of kaons which originate from K^{*0} decay

Efficiency to reconstruct an additional charged pion track

Measurement of f_K, F_K

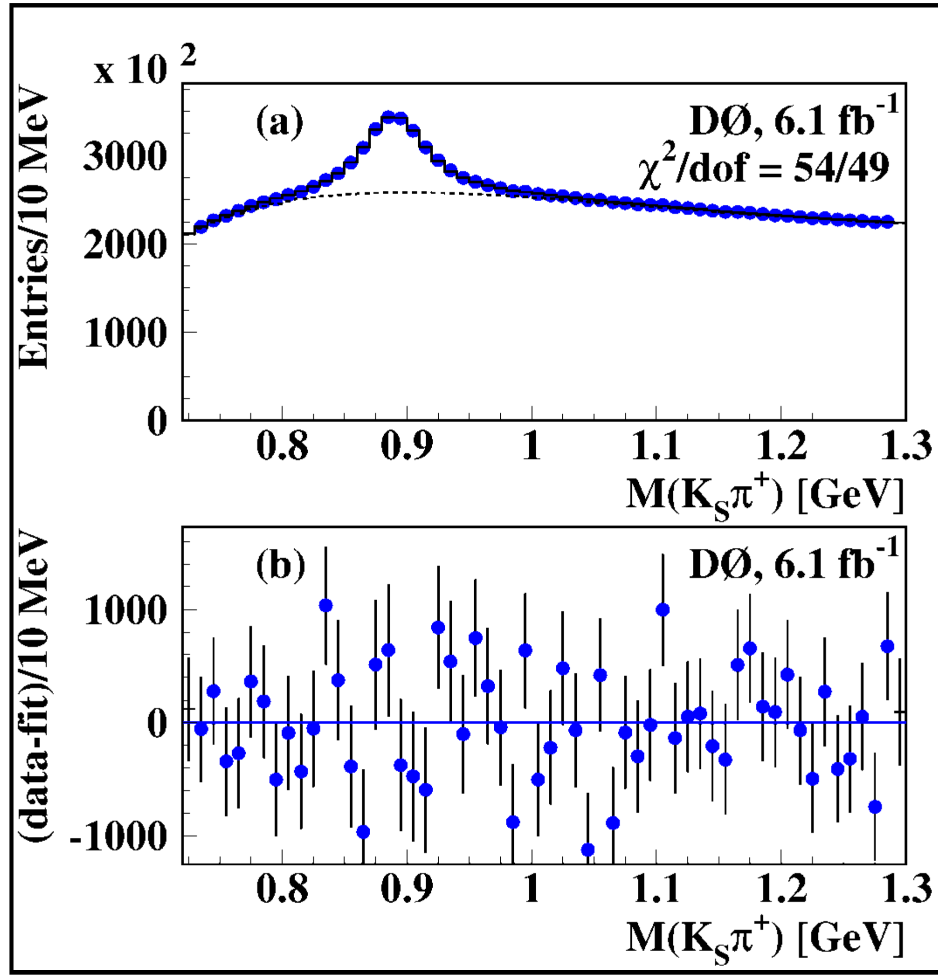
We also select decay $K^{*+} \rightarrow K_S \pi^+$;

- We have:

$$N_{K^{*+}} = N_{K_S} R(K^{*+}) \varepsilon_c$$

Fraction of K_S mesons which originate from K^{*+} decay

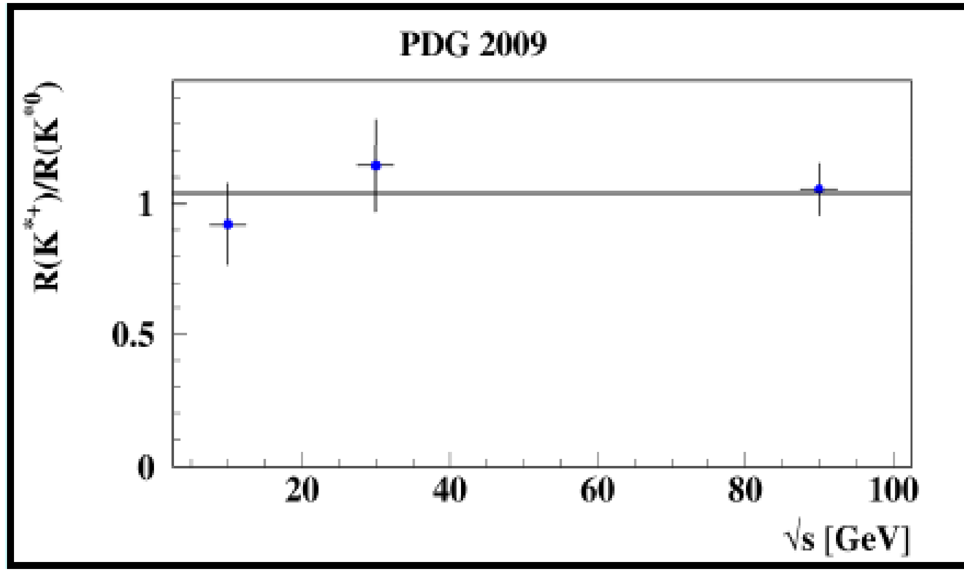
Efficiency to reconstruct an additional charged pion track



Measurement of f_K, F_K

R(K^{*+}) = R(K^{*0}) due to isospin invariance:

- Verified with the available data on production of K^{*+} and K^{*0} in jets at different energies (PDG);
- Also confirmed by simulation;
- Related systematic uncertainty 7.5%



$\varepsilon_0 = \varepsilon_c$ because the same criteria are used to select the pion in $K^{*+} \to K_S \pi^+$ and $K^{*0} \to K^+ \pi^-$

- Verified in simulation;
- Related systematic uncertainty 3%;

Measurement of f_K, F_K

With these conditions applied, we obtain f_K , F_K as:

$$f_K = \frac{N(K_S)}{N(K^{*+})} f_{K^{*0}}$$

$$F_K = \frac{N(K_S)}{N(K^{*+})} F_{K^{*0}}$$

- **The same values $N(K_S)$, $N(K^{*+})$ are used to measure f_K , F_K ;**

We assume that the fraction $R(K^{*0})$ of charged kaons coming from $K^{*0} \to K^+\pi^-$ decay is the same in the inclusive muon and like-sign dimuon sample;

- **We verified this assumption in simulation;**

We assign a 3% systematic uncertainty due to this assumption;

Measurement of f_π, F_π

- We use as an input:
  - Measured fractions f_K , F_K;
  - Ratio of multiplicities of pion and kaon n_π / n_K in QCD events taken from simulation;
  - Ratio of multiplicities of pion and kaon N_π / N_K in QCD events with one additional muon taken from simulation;
  - Ratio of probabilities for charged pion and kaon to be identified as a muon: $P(\pi \to \mu) / P(K \to \mu)$;
  - Systematic uncertainty due to multiplicities: 4%
- We obtain f_π , F_π as:

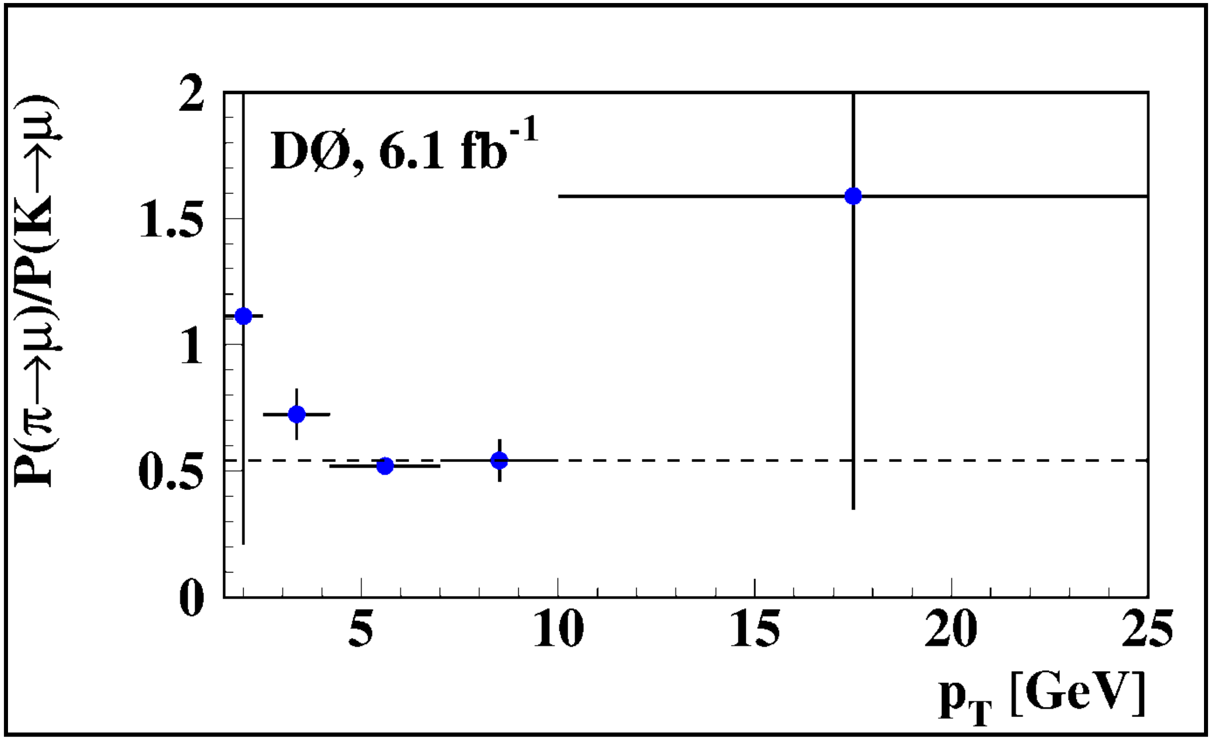
$$f_\pi = f_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{n_\pi}{n_K}$$

$$F_\pi = F_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{N_\pi}{N_K}$$

Measurement of P(π→μ)/ P(K→μ)

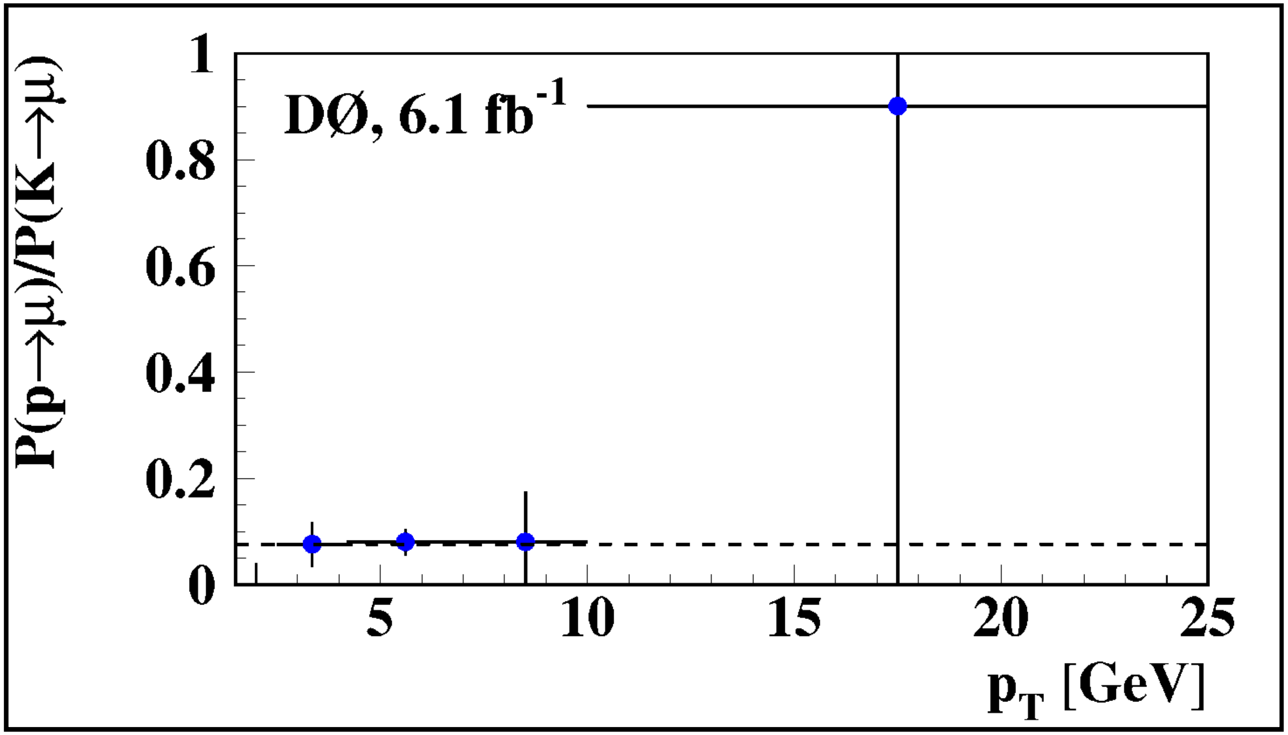
The ratio of these probabilities is measured using decays $K_S \to \pi^+ \pi^-$ and $\phi(1020) \to K^+ K^-$;

- We obtain: $P(\pi \to \mu) / P(K \to \mu) = 0.540 \pm 0.029$



Measurement of f_p, F_p

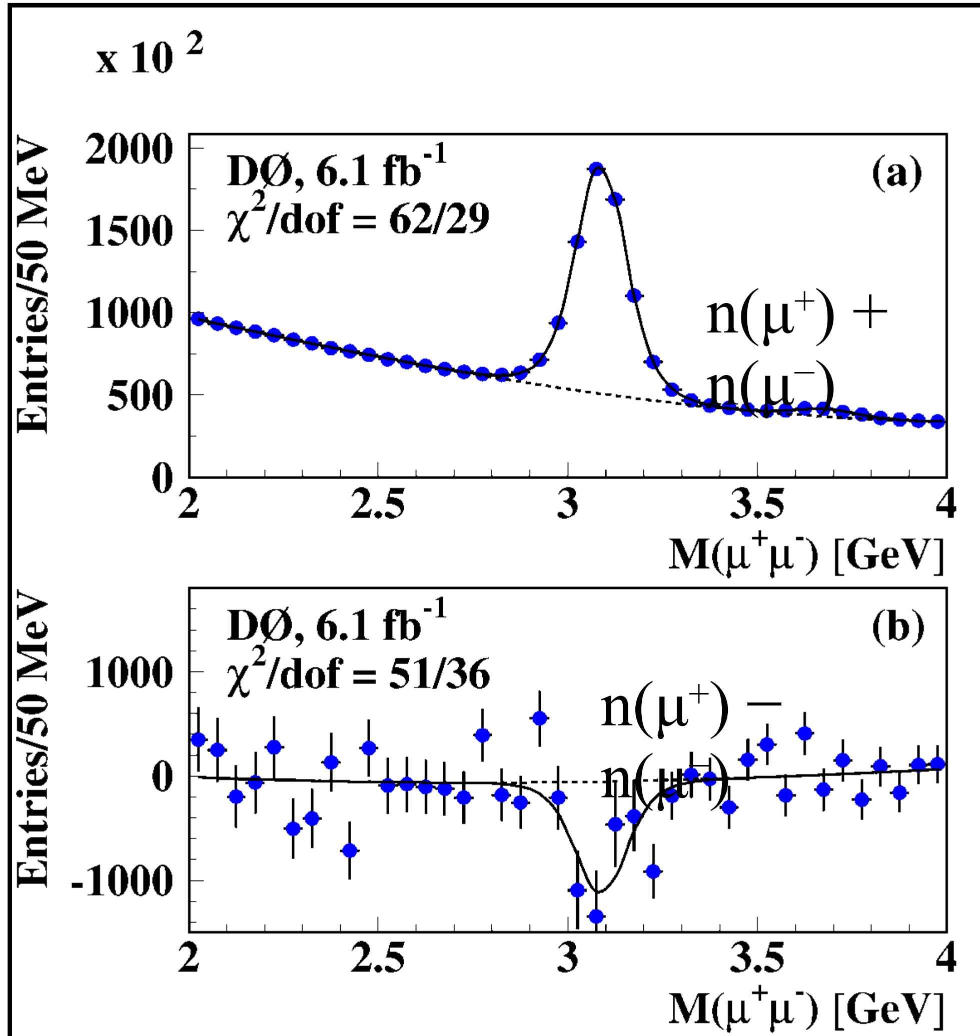
- Similar method is used to measure the fractions f_p , F_p ;
- The decay $\Lambda \rightarrow p\pi^-$ is used to identify a proton and measure $P(p\rightarrow\mu)/P(K\rightarrow\mu)$;
- We obtain: $P(p\rightarrow\mu)/P(K\rightarrow\mu) = 0.076 \pm 0.021$



Muon Reconstruction Asymmetry

We measure the asymmetry of muon reconstruction using decays $J/\psi \to \mu^+\mu^-$;

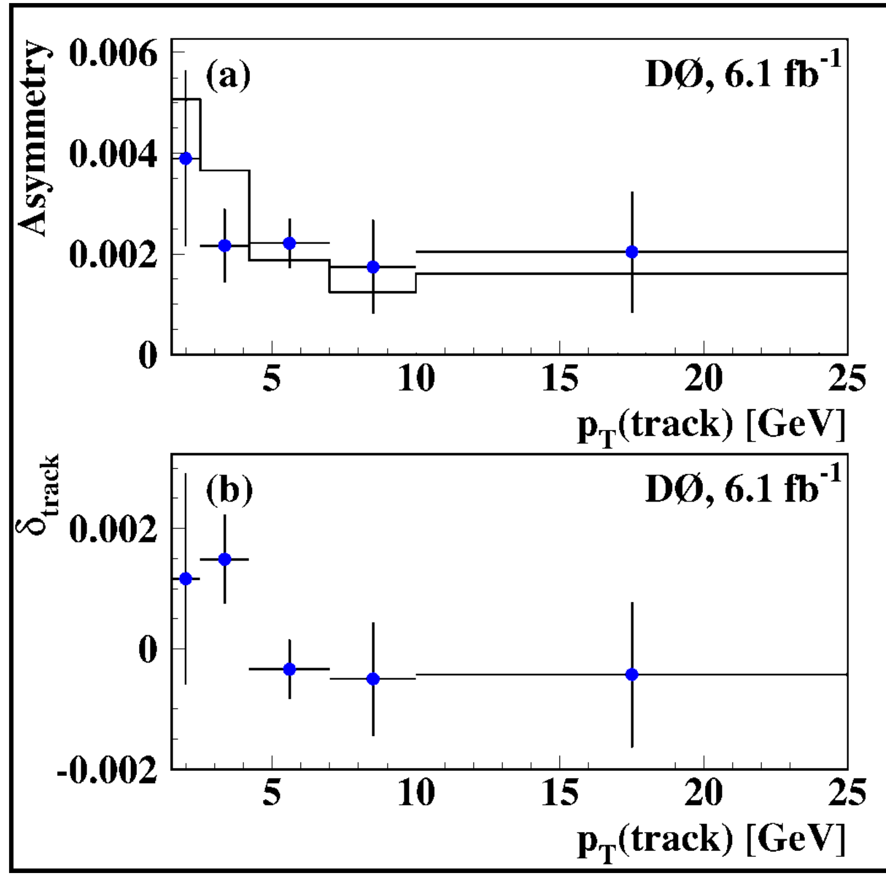
- Select events with only one identified muon and one additional track;
- Build J/ψ meson in these events;
- Extract muon reconstruction asymmetry from the difference in the number of events with positive and negative muons.



Track Reconstruction Asymmetry

- We measure track reconstruction asymmetry using events with one muon and 1 additional track;
- We compute the expected track asymmetry using the same method as in the main analysis, and we compare it with the observed asymmetry;
- The difference $\delta = a_{trk} - a_{exp}$ corresponds to a possible residual track reconstruction asymmetry;
- We find the residual track reconstruction asymmetry consistent with zero:

$$\delta = (+0.011 \pm 0.035)\%$$



Processes Contributing to *a* and *A*

$$a - a_{bkg} = kA^b_{sl}$$
$$A - A_{bkg} = KA^b_{sl}$$

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

Process	a	A
$\bar{B}^0_q \to B^0_q \to \mu^+ X$	Yes	Yes
$b \to c \to \mu^+ X$	Yes	Yes
$B \to \mu^+ X$ (without oscillation)	Yes	No
$c \to \mu^+ X$	Yes	No

All processes except $\bar{B}^0_q \to B^0_q \to \mu^+ X$ are charge symmetric, therefore dilute the values of a and A by contributing in the denominator of these asymmetries.

Processes Contributing to *a* and *A*

	Process	Weight
T_1	$b \to \mu^- X$	$w_1 \equiv 1.$
T_{1a}	$b \to \mu^- X$ (nos)	$w_{1a} = (1 - \chi_0) w_1$
T_{1b}	$\bar{b} \to b \to \mu^- X$ (osc)	$w_{1b} = \chi_0 w_1$
T_2	$b \to c \to \mu^+ X$	$w_2 = 0.113 \pm 0.010$
T_{2a}	$b \to c \to \mu^+ X$ (nos)	$w_{2a} = (1 - \chi_0) w_2$
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (osc)	$w_{2b} = \chi_0 w_2$
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_3 = 0.062 \pm 0.006$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+ \mu^-$	$w_4 = 0.021 \pm 0.001$
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_5 = 0.013 \pm 0.002$
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_6 = 0.660 \pm 0.077$

Consistency Tests A-C

- Test A: Using only the part of the data sample corresponding to the first 2.8 fb^{-1}.

- Test B: In addition to the reference selections, requiring at least three hits in muon wire chamber layers B or C, and the χ^2 for a fit to a track segment reconstructed in the muon detector to be less than 8.

- Test C: Since the background muons are produced by decays of kaons and pions, their track parameters measured by the central tracker and by the muon system are different. Therefore, the fraction of background strongly depends on the χ^2 of the difference between these two measurements. The requirement on this χ^2 is changed from 40 to 4 in this study.

Consistency Tests D-F

- Test D: The requirement on the transverse impact parameter is changed from 0.3 to 0.05 cm, and the requirement on the longitudinal distance between the point of closest approach to the beam and the associated primary vertex is changed from 0.5 to 0.05 cm (this test serves also as a cross-check against the possible contamination from muons from cosmic rays in the selected sample).
- Test E: Using only low-luminosity events with fewer than three primary vertices.
- Test F: Using only events with the same polarities of the solenoidal and toroidal magnets.

Consistency Tests G-J

- Test G: Changing the requirement on the invariant mass of the two muons from 2.8 GeV to 12 GeV.
- Test H: Using the same muon p_T requirement, $p_T >$ 4.2 GeV, over the full detector acceptance.
- Test I: Requiring the muon p_T to be $p_T < 7.0$ GeV.
- Test J: Requiring the azimuthal angle ϕ of the muon track be in the range $0 < \phi < 4$ or $5.7 < \phi < 2\pi$. This selection excludes muons directed to the region of poor muon identification efficiency in the support structure of the detector.

Consistency Tests K-N

- Test K: Requiring the muon η be in the range $|\eta| < 1.6$ (this test serves also as a cross-check against the possible contamination from muons associated with the beam halo).
- Test L: Requiring the muon η be in the range $|\eta| < 1.2$ or $1.6 < |\eta| < 2.2$.
- Test M: Requiring the muon η be in the range $|\eta| < 0.7$ or $1.2 < |\eta| < 2.2$.
- Test N: Requiring the muon η be in the range $0.7 < |\eta| < 2.2$.

Consistency Tests O-P

- Test O: Using like-sign dimuon events passing at least one single muon trigger, while ignoring the requirement of a dimuon trigger for these events.
- Test P: Using like-sign dimuon events passing both single muon and dimuon triggers.